DOCUMENTATION OF EFFECTIVENESS IN OIL SPILL RESPONSE

Experience with efficiency in mechanical recovery in oil spill response

Norwegian Governmental Forum for Cooperation on R&D concerning Oil Spill Response by The Norwegian Centre for Oil Spill Preparedness and Marine Environment

Report No.: 2021-0786, Rev. 01
Document No.: 1168506
Date: 2021-11-24

Project name:	Documentation of effectiveness in oil spill response	DNV AS Energy Systems
Report title:	Experience with efficiency in mechanical recovery in oil spill response	Environmental Risk Management-4100-NO
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Date of issue:	2021-11-24	
Project No.:	10293242	
Organisation unit:	Environmental Risk Management-4100-NO	
Report No.:	2021-0786, Rev. 01	
Document No.:	1168506	

Applicable contract(s) governing the provision of this Report:

Objective:

Experience with efficiency for mechanical recovery in oil spill response operations

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Keywords:

Oil spill, efficiency, mechanical recovery

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
01	24.11.2021	Minor adjustments	HPDAHL	TVEDT	TJEN
0	10.09.2021	Final issue	HPDAHL	BRUDE	TJEN
A	27.08.2021	First draft issue	HPDAHL	BRUDE	

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TERMS AND DEFINITIONS

Mechanical containment and recovery process:

Phase	Term	Definition
	Slick thickness (mm)	Thickness of the oil/emulsion on the surface of the water, assumed to be uniform
	Skimming speed (knots)	How fast the system advances while skimming
	Swath width (m)	Distance between the two leading ends of the containment system/boom
	Encounter rate (l^3/hour or m^3/day	Amount of oil contained and directed to the skimmer per unit of time (function of slick thickness, skimming speed, and swath width)
Containment	Throughput efficiency (%)	oil encountered relative to amount recovered (some will escape before reaching skimmer)
	Total oil recovered (m^3)	Volume of oil/emulsion recovered by the system
	Total fluids recovered (m^3)	Volume of fluids recovered (oil/emulsion + water)
	Skimmer pump rate (l/h or m3/day)	Volume of fluids skimmer can pump per unit of time (manufacturer-designated "nameplate")
Recovery	Oil recovery efficiency (%)	Oil/emulsion recovered relative to the total volume of fluid recovered (oil/emulsion + water)
	Primary storage (m^3)	Volume of fluids that can be retained without offloading (onboard, or in a storage device tethered to skimming vessel)
	Emulsion breaker efficiency (%)	% of emulsion recovered that are separated in oil/water by emulsion breaker
	Decant pump rate (l/m or m3/day)	Volume of free water pumped (decanted) per unit of time.
	Decant efficiency (%)	% of free water recovered that is discharged through decanting
	Secondary storage (m^3)	Storage device to which fluids collected in primary storage are transferred
	Transit time (min/hours)	Time to move primary storage (either on board or separate unit) to secondary storage and back
	Discharge pump rate (l/h or m3/day)	Rate at which recovered fluids are transferred from primary to secondary storage
	Offload time (h)	Time spent to offload oil to secondary storage (function of primary storage volume and discharge pump rate)
Storage	Rig/derig time	Time spent at secondary storage from arrival until departure, except for actual offload time (tie up, connecting and disconnecting hoses etc.

1 SUMMARY

The report summarizes the results of a literature study of experiences with efficiency of mechanical recovery during oil spill events. The report has been prepared for the Norwegian Governmental Forum for Cooperation on R&D concerning Oil Spill Response (Statlig samarbeidsforum FoU oljevern, hereafter The Forum) by DNV and SINTEF. The Forum includes three Norwegian governmental agencies: The Norwegian Centre for Oil Spill Preparedness and Marine Environment, The Norwegian Coastal Administration and The Norwegian Environment Agency.

The goal of the study has been to obtain reliable and empirical documentation of efficiency from mechanical recovery operations based on experiences from historic accidental oil spills and spill responses. The study focuses on mechanical recovery from the water surface in marine coastal and offshore waters. For the study, a total of nine scenarios were selected, providing a variety in spill size, duration, oil type, spill location and recovery strategy. The spill cases were selected in cooperation with the Forum.

The key questions have been:

- How much of the total oil spill was mechanically recovered at sea?
- How much oil available for mechanical recovery was recovered?
- Which factors (internal and external) affected/limited the operation?

Due to the scope of this study, the availability and quality of detailed information proved to be the most critical criteria and the most difficult to obtain. Available data is often limited to gross estimates of spilled and recovered oil. Information regarding response strategies, number, and type of response systems at sea, oil properties and fate, weather, and sea states etc. along the actual timeline of the response operation is often sparse and general.

Efficiency of mechanical recovery based on available oil on sea surface was carried out by using SINTEF’s Oil Weathering Model (OWM). The model considers factors such as evaporation and down-mixing of oil following a spill. The approach and findings should be viewed as a supplement to the existing literature on the subject.

Data availability and quality varies among scenarios as well as there might be inconsistency between sources reporting on the same incident. A potential unclarity is linked to the reporting of pure oil vs. oil/water mixture. It is not always clear if the recovered volume is one or the other or a combination. Based on this, the actual numbers should be read cautiously.

Several of the cases report of significant collection of free water from the recovery process, a factor that also add to the uncertainty of the oil budgets. It was not reported that recovered free water in primary storage tanks hindered recovery. All the cases demonstrates that objectives, strategies, and tactics in oil spill response involves trade-offs between advantages (pros) and disadvantages (cons) in the response. All the cases demonstrate that oil spill response remains a consequense-mitigating, and not an consequense-eliminating, measure.

A summary of the findings is presented in Table 1-1. When estimating recovery as percentage of the spilledvolume, the efficiency ranges from 4 – 75 %. When estimating the recovery in percentage of available oil, the efficiency increases noticeably or significantly in all cases. The efficiency is in several cases also higher than the 10 – 30 % “rule of thumb” that is often referred to. The results are sensitive to the selected cases, and the data does not support a further break-down of the efficiency estimate on system level.

Table 1-1 Overview of the spills, estimated recovery ratios and reported limiting factors for mechanical recovery.

	Year	Name	Type of incident/spill	Recovery of spilled oil (%)[a)]	Recovery of available oil (%)[b)]	Reported limiting factors for mechanical recovery
Petroleum incidents	2010	Macondo[c)]	Blowout offshore (subsea)	4 %	10 %	• Response strategy • Aerial misguiding • Debris/seaweed • Operational restrictions
	2009	Montara[d)]	Blowout offshore (topside)	9 %	13-22 %	• Response strategy • Oil properties
	2003	Draugen	Spill from pipe offshore (subsea)	23 %	44-51 %	• Delayed response • Surveillance/remote sensing • Slick patchiness
Ship incidents	2011	Godafoss	Ship grounding	57 %	63 %	• Low temperatures and sea ice
	2011	Golden Trader[e)]	Ship collision	9 %	33 %	• Oil properties • Weather conditions • Strategy/decision making
	2009	Full City	Ship grounding	10 %	11 %	• Weather conditions • Nearshore
	2004	Rocknes	Ship grounding	31 %	32-35 %	• Nearshore • Tidal currents • Tactics
	2003	Fu Shan Hai	Ship collision	75 %	80 %	• Oil properties • Strategy/decision making • Weather conditions
	2002	Prestige	Ship (tanker) listing followed by breaking in two	41 %	45 – 57 %	• Oil properties • Strategy/decision making • Weather conditions

Footnotes to Table 1-1:
a) Estimated recovery ratio (%) by mechanical recovery at sea of the total reported spill volume.
b) Estimated recovery ratio (%) by mechanical recovery at sea of the spill volume predicted available on the sea surface.
c) Chemical dispersion was used in addition to mechanical recovery.
d) Surface and subsea chemical dispersion and in-situ burning was used in addition to mechanical recovery.
e) Simplified calculation due to diverging data sources.

An oil spill incident and the following recovery phase are often complex and influenced by numerous factors, effecting all aspects from decision-making to recovery efficiency. The nature of the spill itself, like spill type, oil type and spilled volume, defines the framework for the operational strategy. Oil properties is a key factor, which in combination with weather conditions and sea states, may have a significant impact on the decisions regarding both response strategies, tactics, and equipment. Weather and sea-states and other nature-given factors on the scene such as wind, waves, currents, temperatures, visibility, and daylight/darkness played a role in all cases, either in the way that the conditions were favourable for mechanical response at sea the whole time, or part of the time. The evaluations indicate that HSE-considerations and protection of response equipment etc. are prioritized over pursuing recovery in marginal conditions.

HSE related factors are often related to the topics discussed above, and in the case studies HSE were given the highest priority, often based on a watchful and pragmatic approach. Mechanical recovery operations also involve handling of heavy equipment on slippery decks at sea, with the hazards involved. As the case studies indicate, competence and skills in handling the equipment, and the insight of when to stop or change the ongoing operation is key.

The case studies clearly indicate the importance of clear command, control, and communication structure, and that the challenges increase with the scale of the response. The case studies underline the importance of competence, training, and skills for involved personnel both individually and organizational on all levels. A well-managed operation is also closely related to having a good overview and understanding of the situation (operational picture). Remote sensing is a vital source of support for incident management as well as individual response systems. In several cases the spill volumes were underestimated in the initial phases, or there were challenges tracking the spill.

In all the cases mechanical recovery was part of the tactical plan, either exclusively or in combination with dispersant application and in situ burning. Where mechanical recovery was the sole strategy, the tactical priority would typically be to recover the oil close to the source to limit spreading and further impact. For the ship incidents this normally include emptying the remaining oil from the ship and inclusion booming, where the ship is encircled with booms. To achieve maximal effect from inclusion booms, short response time and favourable conditions are required. Since the ship incidents often happened close to shore and in bad weather various parts of the spill in most cases was not contained by this tactic, and open water recovery systems was used to combat drifting oil slicks. In these cases, the at sea recovery often was surpassed by the following, large scale shoreline clean-up operations.

The available documentation from the historic oil spills does not make it possible to assess the performance of the different systems that have been used. Further, it is not possible to assess the level of effort in the combat action. Questions such as whether more systems or other kind of systems could have increased the overall performance and efficiency, cannot be answered clearly. To better be able to give answers to these aspects in the future, it is recommended that guidelines are developed for reporting of effort and efficiency during oil spill combat actions.

2 INTRODUCTION

2.1 Background and purpose

This report summarizes the results of a literature study of experiences with efficiency of mechanical recovery during oil spill events. The report has been prepared for the Norwegian Governmental Forum for Cooperation on R&D concerning Oil Spill Response (Statlig samarbeidsforum FoU oljevern, hereafter The Forum) by DNV and SINTEF. The Forum includes three Norwegian governmental agencies: The Norwegian Centre for Oil Spill Preparedness and Marine Environment, The Norwegian Coastal Administration and The Norwegian Environment Agency.

The Norwegian Centre for Oil Spill Preparedness and Marine Environment is a subordinate agency reporting to the Norwegian Ministry of transport and communications. The Centre's mission is to be a leading Centre of competence in the fields of oil spill preparedness and marine debris, both nationally and internationally. The Centre is to promote best available scientific and experience-based knowledge and be a catalyst for cost-effective and environmentally friendly technologies, methods, and other measures in the combating of oil spills and marine litter.

The Norwegian Coastal Administration is the Norwegian Ministry of Transport's agency for maritime transport, maritime safety, ports, and acute pollution preparedness. The Norwegian Coastal Administration works actively for an effective and safe maritime transport by maintaining the transport industry's need for navigability and effective ports. The Norwegian Coastal Administration prevents and mitigates the harmful effects of acute pollution and contributes to a sustainable development of the coastal zone.

The Norwegian Environment Agency is a directorate under the Ministry of Climate and Environment, with obligations to exercise authority, carrying out the policy of the Government, professional guidance, and supervision. The primary task of the Petroleum Section in the Environment Agency is to process applications for permit according to the Pollution Control Act, give permission to the activities with specific terms, issue regulations and set requirements for oil spill contingency.

The purpose of the Forum is to promote more environmentally friendly and efficient national oil spill preparedness and response. By identifying and promoting knowledge gaps and research needs the forum shall foster coordinated and cost-effective research and development initiatives of high relevance to operational preparedness and response.

2.2 Scope of work

The goal of the study has been to obtain reliable and empirical documentation of efficiency from mechanical recovery operations based on experiences from historic accidental oil spills and spill responses.

The study focuses on mechanical recovery from the water surface in marine coastal and offshore waters. Both spills from ship incidents and petroleum activities have been studied, covering a total of 9 spill cases from Norway, Sweden, Denmark,Spain, France, USA, and Australia.

The study takes a holistic approach, focusing on reported or estimated efficiency at system level or for the overall response, depending on the data available. To document potential or reported capacities for single system components involved in the response, e.g., a particular skimmer pump, has not been within the scope of this study.

The key questions have been:

- How much of the total oil spill was mechanically recovered at sea?
- How much of oil available for mechanical recovery was recovered?
- Which factors (internal and external) affected/limited the operation?

The general implications of these questions are discussed further in chapter 3. The case studies are then presented in chapter 4 and discussed in chapter 5. Conclusion and recommendations are presented in chapter 6.

2.3 Methodology

2.3.1 Project execution

The project has been carried out as a desktop study during spring and summer of 2021. Due to the complexity of the topic and the need for a good framework for the study, the project started with meetings between the Forum and DNV/SINTEF. In the initial process the purpose, scope and limitations of the study was discussed and aligned, and potential sources of information such as existing literature, databases and online resources was evaluated, in addition to internal information. Key definitions and methodical framework were discussed and established, as well as selection criteria for the spill cases to be included in the study. Based on an iterative process in the project, eventually 9 spill cases were chosen to be included in the study. An overview of information sources used in the screening phase are listed in Table 2-1.

Table 2-1 Information sources reviewed in the initial screening process.

Source	Type	URL
CEDRE	Database of spill incidents and threats in waters around the world.	http://wwz.cedre.fr/en/Resources/Spills
ITOPF	Case Studies	https://www.itopf.org/in-action/case-studies/
IOPC Funds	Overview of incidents	https://iopcfunds.org/incidents/incident-map/
Norwegian Coastal Administration	Overview of NCA-lead responses since 2002 (Norway)	https://www.kystverket.no/oljevern-og-miljoberedskap/aksjoner/
HELCOM	Overview over major incidents in the Baltic	https://helcom.fi/baltic-sea-trends/maritime/accidents/
EMSA	Spill response options and case studies	http://emsa.europa.eu/csn-menu/items.html?cid=14&id=486
Marine Pollution Bulletin 163 (2021) 111848	Article: Effectiveness of mechanical recovery for large offshore oil spills (D.S.Etkin, T.J.Nedwed)	https://www.journals.elsevier.com/marine-pollution-bulletin
NOAA	Oil spill case histories 1967 - 1991	https://repository.library.noaa.gov/view/noaa/1671

In the next phase each of the cases were assessed based on the identified literature and documentation. For some of the cases supplementary information was collected in meetings with informants with relevant personal experience or insight in one or several of the incidents/response operations. The applied sources of information are specified in the introduction of each spill case.

2.3.2 Selection of cases

Oil spill response operations are in many ways unique, both regarding the spill incident, the response measures taken and the context and conditions it happens in. Consequently, any study of oil spill recovery efficiency will be sensitive to which cases that are included in the assessment.

In this study the following criteria has been used for prioritizing and selecting the cases:

- Type of response: Mechanical containment and recovery at sea
- Type of incident: Accidental acute oil spills - both ship incidents and petroleum industry related
- Type of release: Both point release and continuous release
- Type of oil: Both fuel oils and crude oils
- Geography: Primarily North Americas and Northern Europe
- Year: Newer incidents are prioritized over older incidents
- Documentation: Availability and quality of documentation/informants

These criteria reflect the focus of the Forum´s mandate and attention, addressing incidents and contexts that are relevant for Norwegian oil spill response management. The number of cases selected also reflects the timeframe and resources that was available for the study.

The selected cases only include incidents where recovery took place. It should be noted that there are other cases, for instance the spill at the Statfjord A-platform in 2007, where systems were mobilized but not put to action due to bad weather.

The selected spill cases in the study are listed in Table 2-2.

Table 2-2 Selected spill cases in the study.

Year	Name	Type of incident	Country
2002	Prestige	Ship (tanker) listing followed by breaking in two	Spain
2003	Fu Shan Hai	Ship collision	Denmark
2003	Draugen	Spill from pipe offshore (subsea)	Norway
2004	Rocknes	Ship grounding	Norway
2009	Full City	Grounding	Norway
2009	Montara	Blowout, topside	Australia
2010	Macondo	Blowout offshore (subsea)	USA
2011	Godafoss	Ship grounding	Norway
2011	Golden Trader	Ship collision	Denmark

2.4 Analysis

We have introduced an approach to estimate efficiency of mechanical recovery of oil at sea and used that approach for the oil spill cases defined above. This is a stepwise approach including the following elements:

- Information about the oil spill from available information sources: Amount of oil being released, oil spill scenario (blowout or point release), distance to shore, weather conditions, amounts of oil being recovered at sea, potential other response options (e.g., use of dispersants), amount of oil stranded and/or being recovered on shorelines etc. Some of these parameters are not always well documented and approximations had to be made.

- Information about oil type: Whether it is a crude oil or bunker fuel (or another oil product). For crude oils, which type of crude oil it is. Type of bunker fuel, e.g., is it an IFO 180 or a heavy product like e.g., IFO 650. As a minimum a few key physicochemical data of the oil in question should be available and preferably also some weathering data (e.g., water uptake, viscosity etc.).

- Having an oil budget is a prerequisite for being able to estimate efficiency in oil recovery operations. It should include amounts of oil being recovered at sea and along shorelines (if relevant), oil removed from the surface by other methods (e.g., dispersant use), evaporated oil and oil mixed into the water columns by natural dispersion (most relevant for crude oils) or submerging (most relevant for heavy bunker oils), due to wave activity. In this project the SINTEF Oil Weathering Model (OWM) has been used as an aid to prepare an oil budget (see next bullet point) in cases where the factors mentioned above were not available, e.g. did not contain estimations of evaporation or natural dispersion/submerging.

- The SINTEF OWM has been used to predict weathering properties for the oils as a basis for mass balance predictions including evaporated, naturally dispersed/submerged and surface oil. The relevant oil type in some of these cases was already included in the OWM database. For the cases where the specific oil type was lacking in the database, a similar oil was selected as a "model oil" based on information about the oil type that was spilt (see bullet point above).

- Mass balance: By combining the oil budget with predicted mass balance from the SINTEF OWM it has been possible to prepare mass balances that included figures for mechanical recovery (and other response options if relevant). These are presented as pie charts. The efficiency of mechanical recovery is presented both as a function of the total oil release and as a function of oil available for recovery on the sea surface, where evaporation and oil mixed into the water column as oil droplets or submerged oil have been deducted.

Because we wanted to compare oil recovered mechanically with oil released, we had to perform this analysis based on fresh oil. This means that all volumes (m^3) or weights (tonnes) of weathered oil had to be re-calculated as water-free oil. This may easily introduce inaccuracies because values like water content, degree of weathering etc. must be estimated. However, this analysis was used to quantify and visualize the estimated efficiency of mechanical recovery of oil at sea for the different cases with all uncertainties and limitations as discussed below.

2.5 Limitations

Due to the scope of this study, the availability and quality of detailed information proved to be the most critical criteria and the most difficult to obtain. A few comprehensive overviews of historic oil spills exist, but the level of detail in these overviews regarding mechanical recovery is often limited to gross estimates of spilled and recovered oil. Information regarding response strategies, number, and type of response systems at sea, oil properties and fate, weather, and sea states etc. along the actual timeline of the response operation is often sparse and general.

Post-spill reports from the incidents proved to be the most valuable sources of information for this study. Such reports vary in form, content, and detail, but is often the best source for a recapitulation of the incident and response. For finding recovery efficiency, several shortcomings and potential sources of error still occurs. Firstly, to accurately define the size of a spill may be challenging for several reasons, and often include elements of estimation. Secondly, there is the question of the spill’s availability for mechanical recovery (or other response strategies, or combinations) which is depending on several factors, such as the spill type and -site, the oil properties, and the sea- and weather conditions. These factors will to a large degree decide how much of the spilled oil that evaporates, disperses naturally, or ends up on the shoreline – where in either form it is not available for mechanical recovery at sea. The availability-factor may also be influenced by the availability of suitable response systems, surveillance, and trained responders. Often in post-spill reports the accounting of the fate of the spill does not make such distinctions, and recovery efficiency are typically defined as a percentage of the spilled amount, not a percentage of oil/emulsion available for recovery.

Emulsification, as well as uptake of free water as a biproduct of the recovery process, will affect the amount of recovery, but the reported categories and units for recovered oil are not always clearly specified or known. Typically, the distinction between recovered fluid (oil/emulsion and water), emulsion, or pure oil is vague, or based on estimates. Both weight and volume units may be reported, but they are often inter-converted to one common unit which introduces potential for errors unless the properties of the recovered fluid are known and specified.

Finally, post-spill reports normally only summarize the grand totals of categories such as 1) spilled oil, 2) recovered at sea, 3) recovered on shoreline and 4) remaining oil in the environment. While this reflects the overall outcome of a response, it remains difficult or impossible to backtrack and quantify the contribution from the individual recovery systems involved (normally several). In some cases, recovery numbers are reported for individual systems, but information regarding total time in operation is missing.

If we want to calculate the mass of oil recovered as a function of oil available at the sea surface, processes like evaporation and removal of oil from the surface by wave activity (natural dispersion of oil droplets or submerging of heavy oils) must be included. These processes have originally been estimated for only a few of the cases in this study and the SINTEF OWM has been used to predict these processes (see paragraph 2.4) for the other oils. Such predictions are dependent on the choice of oil and may introduce uncertainties/limitations if there are uncertainties about the oil type and its input data to the model. As a rule of thumb, most crude oils will form small droplets mixed into the upper water column by increasing wave activity. Heavier oils, like bunker fuels, may form larger droplets, lumps or flakes of oil that may be over-washed by wave activity. This submerged oil may come back to the surface (re-surface) if the weather calms down. However, in this project, where real wind data are lacking, we have been running the SINTEF OWM with constant wind (e.g., 5 or 10 m/s) (except for the Draugen spill) and submerged oil has been regarded as not being available for recovery on the surface, even if the wave activity decreases. The predictions presented in this report name oil mixed into the water column as "naturally dispersed", and this should be read as dispersed oil droplets for slightly weathered crude oils and otherwise submerged/over-washed oil for the heavy bunker fuels and highly weathered and emulsified crude oils.

In conclusion there are several potential sources of error and inaccuracy in the existing sources of information when trying to find recovery efficiency in historic events, both overall and on a system level. This introduces a level of uncertainty to the results in this study that must be recognized. Finally, it should be emphasized that due to the unique nature of each spill, comparing only recovery numbers or generalizing based on a few cases, should be avoided. The approach taken in this study and the findings should be regarded as a supplement to existing studies and assessments.

3 EFFICIENCY IN MECHANICAL RECOVERY

3.1 Mechanical containment and recovery at sea

Mechanical recovery is possibly the most widespread technique for combating acute oil pollution in marine environments, and include methods and technologies intended to collect and remove oil and emulsion from the sea surface. Free-floating oil will only seldom form a layer so thick that it can be removed/pumped up directly in an effective way. The spill must normally be contained with booms so that the oil thickness can be increased to a few millimetres or more. Thus, the terms *containment and recovery* are also often used. Numerous variations of mechanical recovery exist, including the technology involved, but the standard approach is a combination of booms and skimmers operated from vessels with storage capacity for the recovered oil.

It is not within the scope of this study to describe the various components, systems, techniques, and tactics that goes into mechanical containment and recovery as such. An overview of mechanical recovery at technical, tactical and operational level is available for instance in the “At-sea containment and recovery. Good practice guidelines for incident management and emergency response personnel” (IPIECA/IOGP, 2015).

3.2 Efficiency – terminology and areas of use

Mechanical containment and recovery aim to physically collect and remove oil or other spilled material from the environment to prevent or mitigate environmental damage. The result of the removing process will consequently reflect the level of achievement. Several terms are used to express this in the literature, such as recovery effectiveness, recovery efficacy, and recovery efficiency. These terms are often used interchangeably, but some nuances have been suggested:

Effectiveness = the ability to produce a result

Efficacy = the ability to produce a desired or intended result

Efficiency = how well the result is produced (ratio)

Typically, efficiency in mechanical recovery in some way relates to the volumes of oil that is removed, rather than to the mitigated consequences for the environment – although consequence mitigation is the ultimate purpose.

Other related terms commonly used in the literature and the oil spill response community in general are *capacity* and *capability.* Capacity is often used to describe a technical potential for certain response systems or system components at given circumstances, while capability normally applies to the overall ability to respond in an adequate manner.

This study focuses on recovery efficiency as the ratio of mechanically recovered oil relative to the oil spilled and oil available for recovery. Other terms and commonly used units that applies to the individual steps and components in the containment and recovery process are listed initially in this report.

Estimations of efficiency has several practical areas of use, such as:

- Planning and dimensioning oil spill preparedness
- Technology development and documentation
- Procurement/sales
- Verification

A comprehensive literature, including research reports, good practices, standards, methodologies, and tools exist for planning, measuring, quantifying, and estimating efficiency (“pre-spill assessments”). Pre-spill assessments may focus on specific technical components in recovery systems, such as pump capacity, the overall recovery system, or the combined efficiency of several systems. Variables such as oil properties, spreading of oil, and weather conditions are often reflected in various detail and complexity.

In comparison, the literature comparing experience with efficiency from real spill incidents seem sparser. “Post-spill assessments” are common, but they focus on the individual spills and its specific circumstances and solution.

A commonly used rule of thumb among oil spill response planners and responders estimates that 10 - 30 % of a spill is a realistic expectation from mechanical recovery at sea. The rest evaporates, mixes into the water, or ends up onshore. In a recently published article in the Marine Pollution Bulletin, a review of large offshore spills estimates that only 2 – 6 % of the spills were collected through mechanical recovery at sea (D.S.Etkin, T.J.Nedwed, 2021). Another study reviewed oil spill responses on moderately sized spills in US waters from 1993 – 2000 found that the majority of spills where mechanical recovery was used had a recovery rate of 50 to 59 % (DeCola, undated). Both reports address several potential sources of errors in the background data.

In Norway NCA routinely perform post-spill assessments that describe the incident and response, including oil budget. The oil budget attempts to quantify the volume and fate of the various fractions in the spill. As described in the previous chapter there are often several challenges when trying to account for spills, and the reporting often focus only on overall fractions – such as total volume recovered at sea. While this says something of the overall recovery at sea, it often does not document efficiency at system level and/or for specific periods of time during the response. Often the main focus in post-spill assessments is on mapping environmental and socio-economic effects of the spills.

3.3 Factors that affect mechanical recovery

There are multiple factors and combination of factors that may affect the efficiency of mechanical recovery at sea. These can be described as external factors that are related to the incident itself, its context, and physical surroundings. Internal factors refer to the response itself, and how it is managed and performed. Internal factors are normally also closely related to preparedness planning and pre-spill preparations on technical and organizational levels.

External factors (environmental and oil behaviour) can be:

- Release volumes
- Oil type and properties
- Evaporation, biodegradation, oil in water dispersions and emulsion
- Oil spreading, and size of the affected area
- Recoverable emulsion volumes
- Duration of the spill event
- Area of release (coastal or offshore)
- Wave hight (start, during and after the spill)
- Ocean currents
- Weather conditions (temperature, wind, precipitation, visibility)
- Other relevant external factors

Relevant internal/operational factors that are important for the efficiency of mechanical recovery can be:

- Prioritizations taken during the response operation – e.g. protection of sensitive environmental resources vs. areas with large amounts of recoverable oil
- Were other response strategies used (in situ burning, efforts to disperse the oil)?
- What types of mechanical recovery systems were used?
- How many systems were available and used?
- Who handled the equipment (affiliation/qualifications)?
- Notification, mobilization, and response time
- What role did remote sensing (monitoring and detection) play?
- System and crew endurance
- HSE challenges (toxic gasses and risk of explosion)
- The hassle-factor
- Storage tank capacity, disposal of oil and emulsion
- Oil-water separation and local decanting rules
- Other relevant operational factors

Factors that can reduce the efficiency of at-sea containment and recovery operations according to the IPIECA/IOGP guideline are listed below:

- the availability of logistical support (including vessels) for an escalating response;
- the likelihood of oil rapidly spreading and fragmenting;
- prevailing environmental conditions (sea state, current, wind);
- the ability of vessels to tow and manoeuvre at low speeds;
- limited encounter rates due to slow boom towing speeds and narrow swath-width;
- offshore temporary storage capacity versus skimmer recovery rates;
- the availability of competent personnel to conduct and support the operation;
- limited field of vision caused by low height of eye above sea level or poor weather; and
- lack of aerial support and communications.

A high level of preparedness can help to overcome these challenges and can enhance and increase the efficiency of the response. Key elements in building response preparedness include:

- understanding the oil's properties, fate, and potential effects;
- use of sensitivity mapping and oil spill modelling (i.e. to predict the trajectory of the spilled oil and where it is likely to have an impact);
- selecting the appropriate equipment for responding to the type of oil spilled;

- training response teams to ensure that they are familiar with the equipment and understand the appropriate response techniques;
- encouraging response teams to build an efficient interface between teams with different roles in the response; and
- periodic exercising including mobilization of response equipment.

3.4 Technological advances

For this study it should also be noted that spill response technology for mechanical recovery at sea has developed and improved over the years. This should be kept in mind when assessing the recovery efficiency of spill cases from different periods. Improvements related to organization, communication, competence, and training etc. are equally important. An overview of technological advances in recent years are given in the report "Assessment of status for research and development. Effective and environmentally friendly methods and technologies in oil spill response – knowledge status" (DNV/SINTEF, 2020).

4 CASE STUDIES

4.1 Macondo / Deepwater Horizon (2010)

4.1.1 Sources of information

Hundreds of documents exist from the Macondo well incident and response. The following sources have been selected:

- National Response Team, 2011: On Scene Coordinator report *Deepwater Horizon* Oil Spill: (PDF) On Scene Coordinator Report Deepwater Horizon Oil Spill | Plinio Tavares - Academia.edu
- CEDRE, 2020. Database of spill incidents and threats in waters around the world. http://wwz.cedre.fr/en/Resources/Spills.
- Dagmar Schmidt Etkin, Tim J. Nedwed, 2021: “Effectiveness of mechanical recovery for large offshore spill”, Marine Pollution Bulletin, https://doi.org/10.1016/j.marpolbul.2020.111848
- Daling et al, 2014: "Surface weathering and dispersibility of MC252 crude oil”. Marine Pollution Bulletin, 87/2014: http://dx.doi.org/10.1016/j.marpolbul.2014.07.005
- Leirvik, F., Daling, P.S., Trudell, K., Parschal, B.,2010: A.Cruise report – Assessment of dispersibility of DWH oil at different stages of weathering. SINTEF report A16062, ISBN 978-82-14-05004-2, 24 pp.
- US Navy, NAVSEA presentation, 2012: PPT - Deepwater Horizon Disaster Response U.S. Navy Supervisor of Salvage and Diving NAVSEA 00C25 PowerPoint Presentation - ID:759670 (slideserve.com)
- Lehr, B., Bristol, S., A. Possolo (Oil Budget Calculator, OBC), 2010. Deepwater Horizon oil budget calculator: a report to the National Incident Command. The Federal Interagency Solutions Group, oil budget calculator science and engineering team. Technical documentation. November 2010, 217 p. Retrieved from OilBudgetCalc_Full_HQ-Print_111110.pdf (restorethegulf.gov)
- Jørgensen, A., 2021: Operating Response experiences, “team Norlense”: Personal communication
- Nilsen, D., 2021: Operating Response experiences, “team NOFI”: Personal communication

4.1.2 Description of the incident

On 20 April 2010, some 66 km off the coast of Louisiana, the oil rig Deepwater Horizon (drilling at the Macondo/MC 252 well in the Gulf of Mexico) suffered an explosion followed by a fire. 17 people were injured, and 11 others reported missing. The US Coast Guard managed to swiftly evacuate 115 of the 126 people on the rig at the time of the disaster.

The rig sank two days later, and the 2 000 to 2 500 m^3 of oil on the rig either burnt off or was released into the sea. A vast mobilization of spill response equipment was rapidly organized, and surveys conducted using underwater remote-operated vehicles (ROVs) reported that 159 m^3 of crude oil a day was leaking from the riser located 1 500 m below the surface.

Figure 4-1 Explosion at the Deepwater Horizon drilling rig 20. April, 2010 off the coast of Louisiana.

A few days later, new estimations revealed that this leak could be five times larger than initially imagined. Thus, 800 m^3 of the crude oil were believed to be leaking into the sea every day. However, when independent experts became involved, the quantity of oil escaping was estimated to be more than 10 times greater: around 10 000 m^3 per day.

The leak was stopped July, 15th. by installing a "capping stack" to the top of the BOP. The well was definitively plugged on September 19th. The DWH / Macondo incident is the largest marine oil spill in the history of the petroleum industry.

Spilled volume estimation

Over the 86 days of leakage, it is assumed that a volume between 700 000 and 860 000 m^3 had leaked from the well. In early August, 2010 a scientific team established placed by the US authorities in charge of assessing the quantity of oil spilt, announced their expected estimate of 779 000 m^3 (4,9 mill bbl.) oil (i.e. ± 10 %), of which 16 % (125 000 m^3 i.e. 820 000 bbl.) was recovered directly as it leaked from the well-head by using "Riser Insertion Tube Tool" – RITT and a "Top-hat" systems that siphoned part of the leaking oil to the Discover Enterprise drillship. Altogether, it is therefore assumed that 655 000 m^3 went into the marine environment (see also total Oil Budget estimates in Figure 4.9).

4.1.3 The oil spill response

The Macondo / DWH incident initiated the largest marine oil spill response operation ever. E.g. on the single most demanding day of the response, over 6 000 vessels, 82 helicopters and 20 fixed wing aircraft and over 47 849 personnelresponders were assigned.

Response strategies

The overall strategy deployed was to prevent the oil from reaching the coast, particularly at sensitive areas in Louisiana.

In addition to traditional mechanical oil recovery at sea (see details below), the following significant combat methods strategies were extensively used offshore:

- Sub-Surface Dispersant Injection (SSDI) at the source: Total 3 000 m^3 dispersant (Corexit 9550) injected. A maximum of 60 m^3 dispersant per day was injected continuously from day 29 until leak was stopped (day 86)
- Surface dispersant application: Total 4 000 m^3 dispersant (90 % C 9550 and 10 % C9527)
    - Spraying from vessels and support ships (total 400 m^3) at the well site near the drill rigs in order to control Volatile Organic Compound (VOCs) that pose a health and safety threat to those crew working at the well site (e.g. RITT and "Top-hat" operations).
    - Fix-wing aerial treatment (total 3 600 m^3), operating offshore more than 5 nm from the source

- In-situ burning (ISB): ISB operations were conducted offshore during calm weather conditions (< 5 m/s wind). More than 400 ISB operations were conducted, and an estimated volume of 40 000 m^3 (250 000bbl) oil were burned.

Figure 4-2 is schematically illustrating the operational area priorities for the different response strategies.

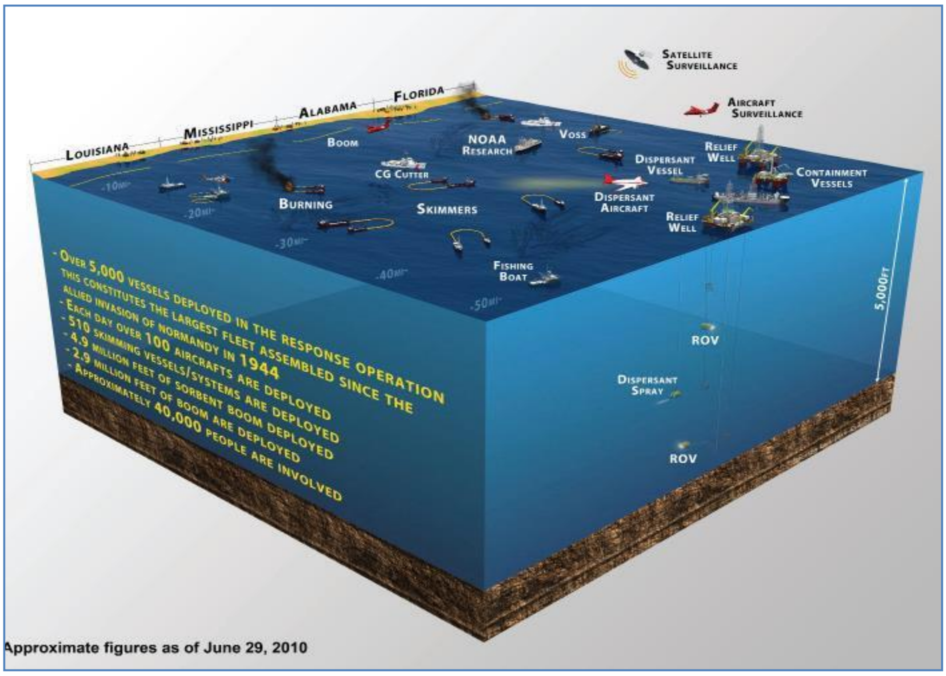


Figure 4-2 Schematics illustrating the operational area for the different response strategies.

Mechanical recovery response

A gigantic armada response of vessels was during the first two month mobilised. By the end of July, over 6 000 ships and 540 barges had been mobilised (Figure 4-3). More than 750 different booms and skimmers systems of all types were used (see examples in Figure 4-4).

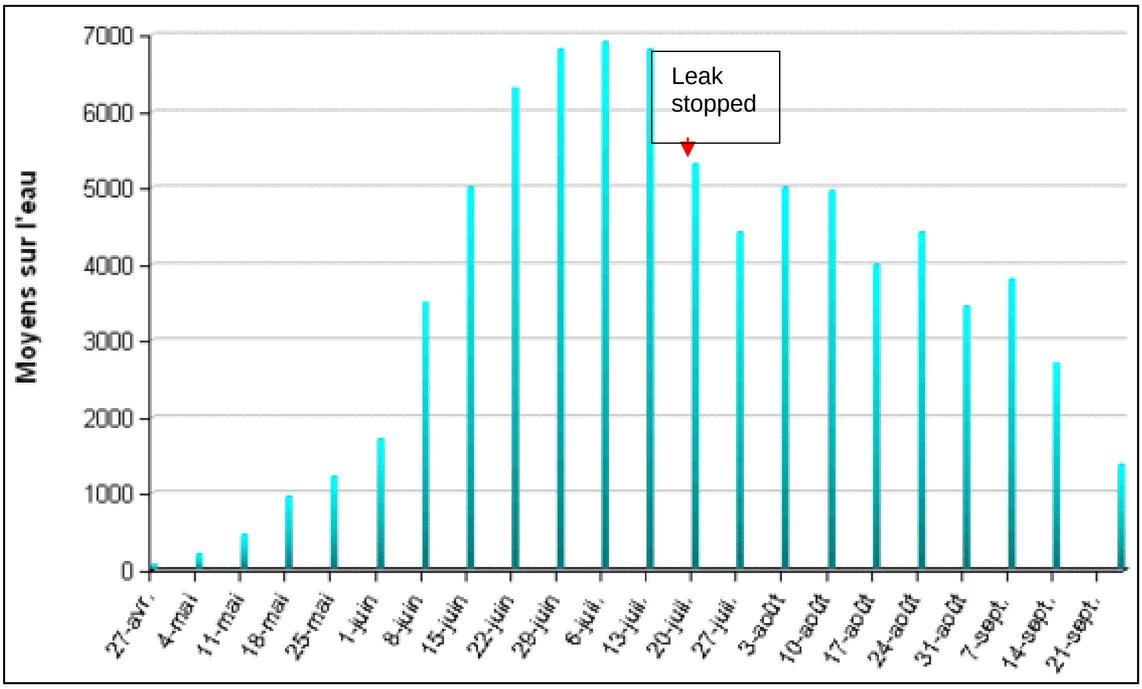


Figure 4-3 Number of vessels / barges onsite during the response period (Cedre, 2020)

Figure 4-4 Examples of mechanical recovery systems involved in the response (offshore).

Not all innovative technologies tested during the response were successful. As an example: At the beginning of July, the 335 m long super tanker "A Whale", had been altered into a gigantic weir-skimmer for conducting oil recovery at sea (funded by Taiwanese owners). The tanker was supposed to be able to pump off a mixture of oil and water, then separate off the water, transferring the oil onto another vessel and discharging the water into the sea. However, after a series of non-conclusive tests, BP did not contract this vessel for its response efforts.

4.1.4 Influencing factors

Location

The location of the DWH rig was 66 km off the coast of Louisiana, where the nearest main operative port for the offshore oil industry is Port Fourchon. The transit time to the spill site vessels were > 6-8 hours, means that the offshore-classified response vessels stayed on site for days to minimize the transit time.

Environmental conditions

Several general restrictions were put on the response vessel operations due to the environmental conditions. E.g.

- No vessel response operations at night / darkness
- No vessel response operations at > 1 m significant wave heights (i.e. > 5-6 m/s wind).

Figure 4-5 shows the wind conditions on site during the entire release (20. April to end of July).

Statistically, only 38 % of the time had wind conditions > 5m/s. This is significant calmer average sea conditions compared to e.g. North Sea / Norwegian Sea average sea conditions where > 85 % of the time have wind above 5 m/s (i.e. breaking wave conditions). Another favourable parameter was the sea temperature of 32 °C.

The presence of patchy areas with seaweed confused the spotter-aircraft by misleading guiding response vessels to dense areas with seaweed that could cause operational trouble for booming confinement and skimmer operations (see Figure 4-6.

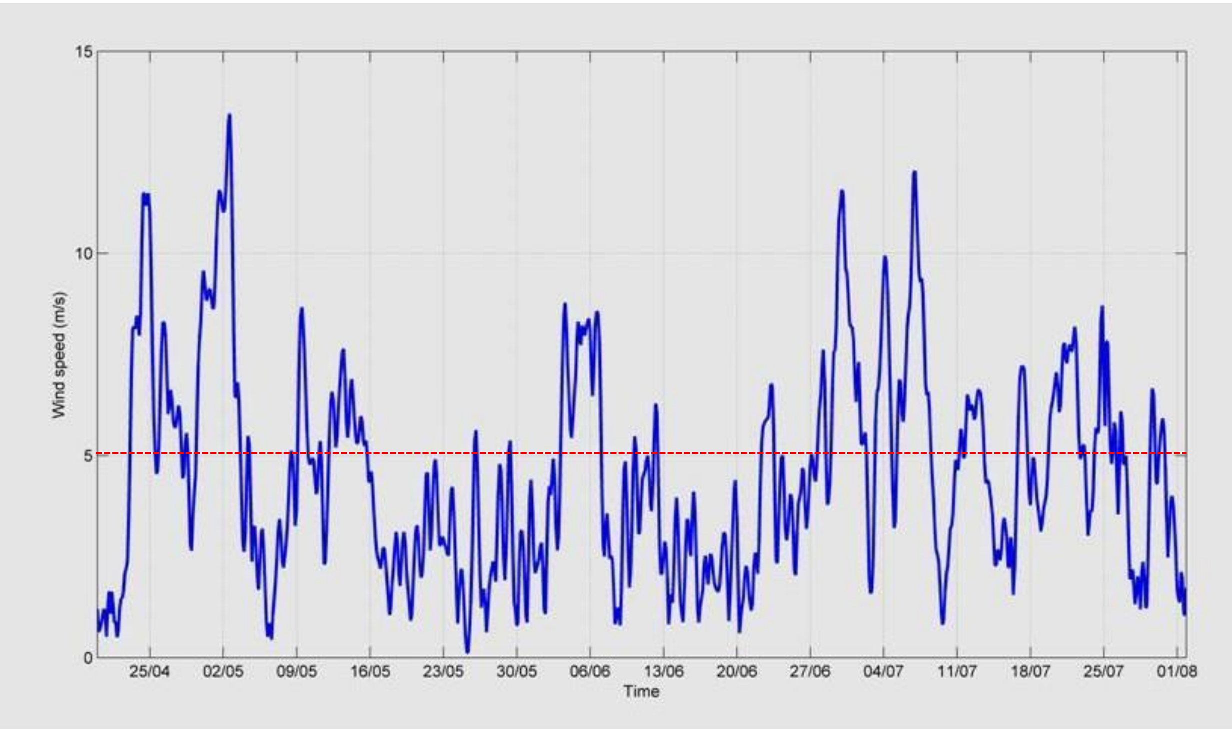


Figure 4-5 Wind conditions on site during the entire release (20. April to end of July). 62 % of this time period had wind <5 m/s.

Figure 4-6 Upper: Patches of "seaweeds" (left) versus patches / area of emulsified oil (right) caused confused misleading guiding from spotter aircraft. Middle / down: Example of seaweed hindered the oil overflow into the Weir Skimmer systems (photos: SINTEF).

Oil properties and oil weathering at sea

The oil properties and oil weathering characteristics of the Macondo MC-252 crude oil was performed by Daling et al 2014. This included comprehensive laboratory bench-scale and flume basin testing of the crude oil weathering properties and dispersant effectiveness. Data generated were used as input for oil weathering modelling (SINTEF OWM) where the oil weathering properties were predicted under different environmental sea-conditions. The laboratory and modelling data were also validated against ground truth samples of surface oil / emulsion taken at different positions from the release source (Leirvik et. al. 2010).

The Macondo oil was a light paraffinic crude oil, with a higher content of volatile components and a lower content of heavy components like asphaltenes and waxes than the most paraffinic North Sea crudes (see example of comparison with the Oseberg crude, Table 4-1 below),

Table 4-1 Oil properties of Macondo crude comparison with Oseberg Blend crude.

	MC 252 DWH crude	Oseberg Blend
Specific gravity (kg/l)	0.833	0.839
Pour point (°C)	- 27	- 24
Viscosity (cSt at 40°C)	4	5
Asphalthenes (wt%)	0.15	0.2
Waxes (wt%)	1.6	2.8
Distillation – TBP curve 150º C+ (vol. % loss) 200º C+ (vol % loss) 250º C+ (vol % loss)	 26.9 38.6 49.7	 22.4 34.4 44.7
Env. Conditions: Sea temperature (June) Sun irradiation (UV -light) Sea state / Wind (% of time > 5 m/s wind)	**GOM** 32º high 38%	**North Sea** 13º lower ca. 85 %

Due to the high content of volatiles and high surface sea temperatures (32 ºC), the SINTEF OWM weathering predictionsof the oil entering the sea surface) show a high degree of evaporative loss (e.g., 45 – 50 vol % evaporation within the first day at sea, see Table 4-7. Other findings from this study show a relative slow emulsification in the calm sea conditions the first days (e.g., water content < 50 vol % within the first day, see Figure 4-8A). The emulsion generated had a low viscosity, giving a high effectiveness of dispersants, and a large “time window” for use of dispersants (> 1 week, see Figure 4-8B). The "time window" for burnability / ignitability was estimated to be up to 4 days after the oil release under gentle sea conditions. For oil released under higher wind conditions (e.g., 7- 10 m/s wind), the degree of natural dispersion become very high for this low viscosity and unstable emulsion (see Figure 4-7).

This shows that all the three surface response options (mechanical recovery, dispersant application and in-situ burning) had a great potential for being effective based on the oil weathering properties of the surface oil / emulsion.

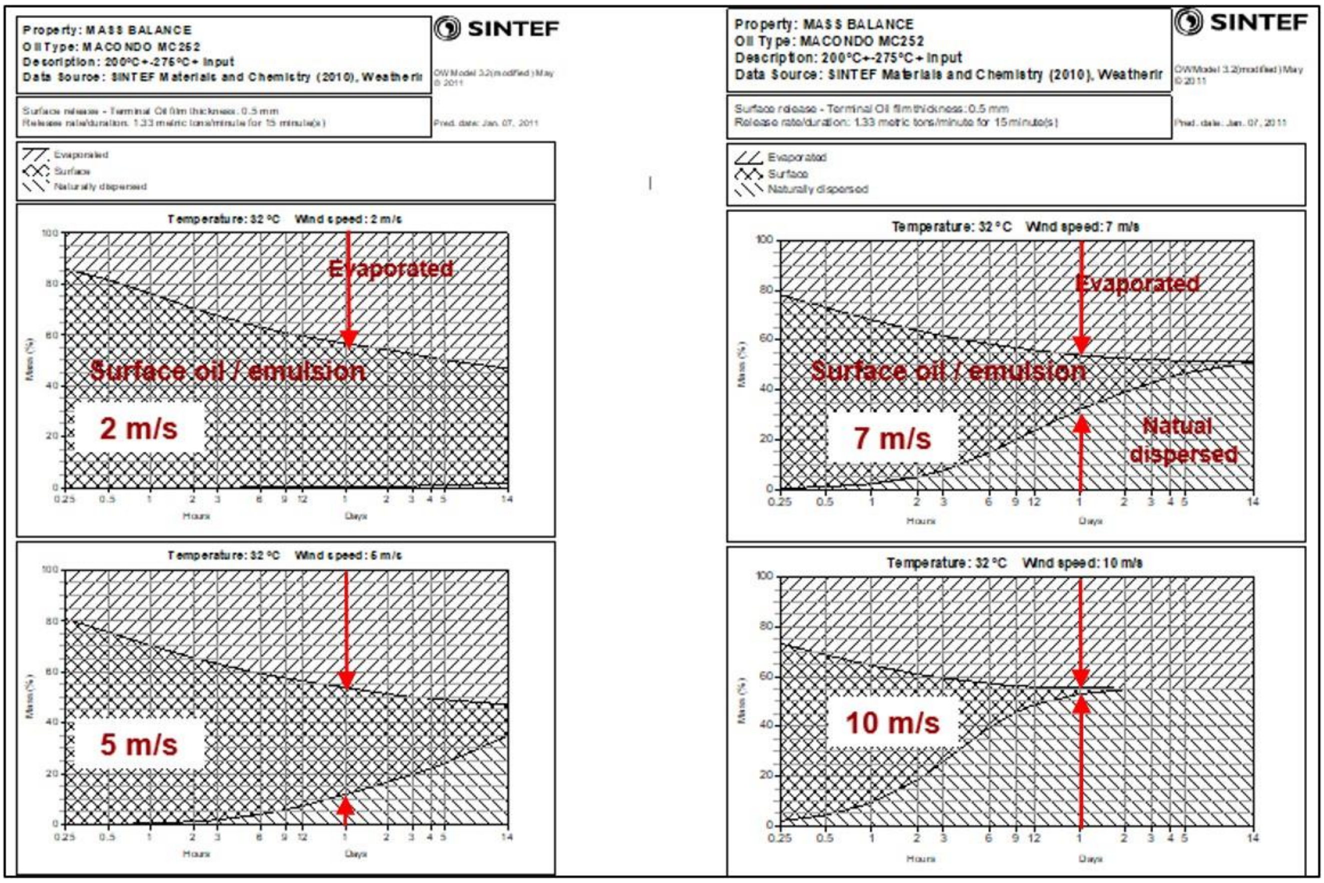


Figure 4-7 Predicted mass balance of Macondo oil at sea surface (32 ºC sea temp.) under different wind conditions.

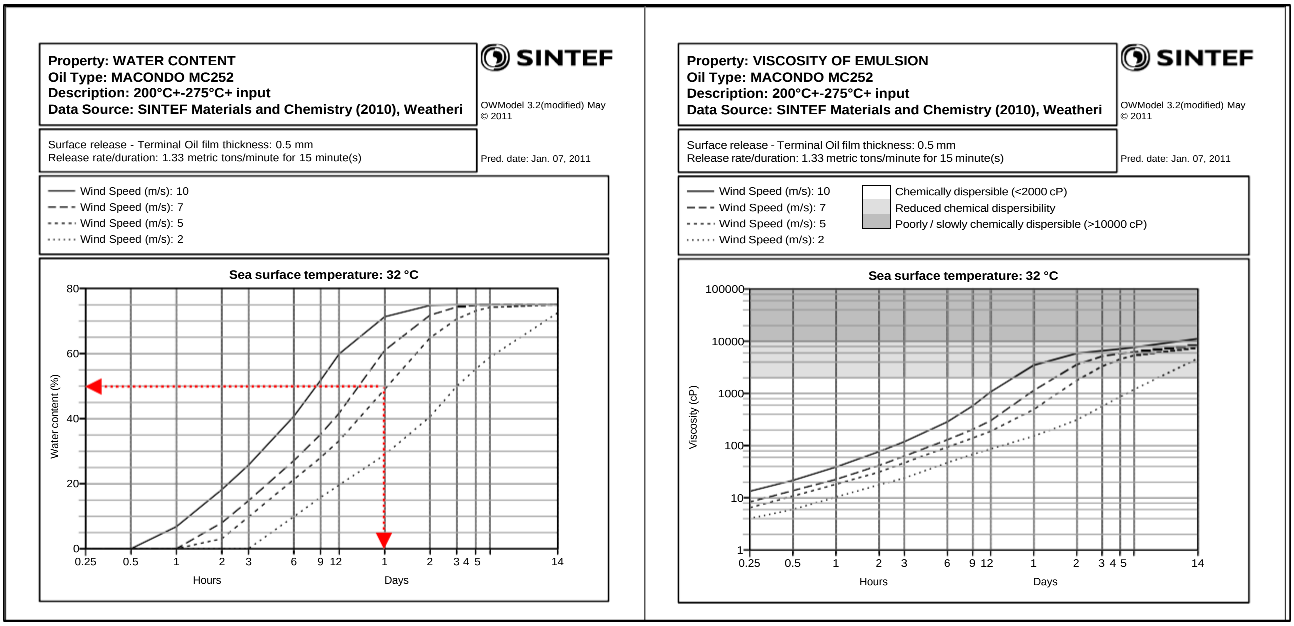


Figure 4-8 Predicted water uptake (A), and viscosity of emulsion (B) at sea surface (32 ºC sea temp.) under different wind conditions

4.1.5 Recovery efficiency

Figure 4-9 shows the official estimate of the total oil budget including physical weathering processes and the tentative efficacy estimate of the different response operations (Lehr et al. November 2010). This "Oil Budget Calculation" is based on an assumed release of 779 000 m^3 (4,9 mill bbl.), where the 16 % (125 000 m^3) recovered directly as it leaked from the well-head (RITT / Top-hat), is excluded in the figure. The calculated amount of oil recovered (pure water-free oil residue) is reported to be 25 000 m^3 (160 000 bbl.). The figure indicates that about 4 % (of the 665 000 m^3 oil released to the environment) was mechanically recovered at sea surface. The more long-term weathering processes (e.g. biodegradation) and fate (e.g. sinking to seabed, stranding onshore) is not included in this budget calculation.

A tentative calculation of the oil available for the response operations on the sea surface (i.e. by eliminating evaporation, dissolution and natural dispersion around the source area and the chemical dispersion due to sub-sea dispersant injection- SSDI at the wellhead), this would tentatively double the efficacy numbers for the response operations (Etkin and Nedwed, 2020). Based on that estimation, they calculated that the mechanical recovery operation would have been contributed to around 5.5 – 8 % of the oil that was available for response on the sea surface. This is, however, still below the general "rule of thumb" that 10 – 30 % of total oil is expected to be mechanical recovered in an oil spill incident (Etkin and Nedwed, 2020).

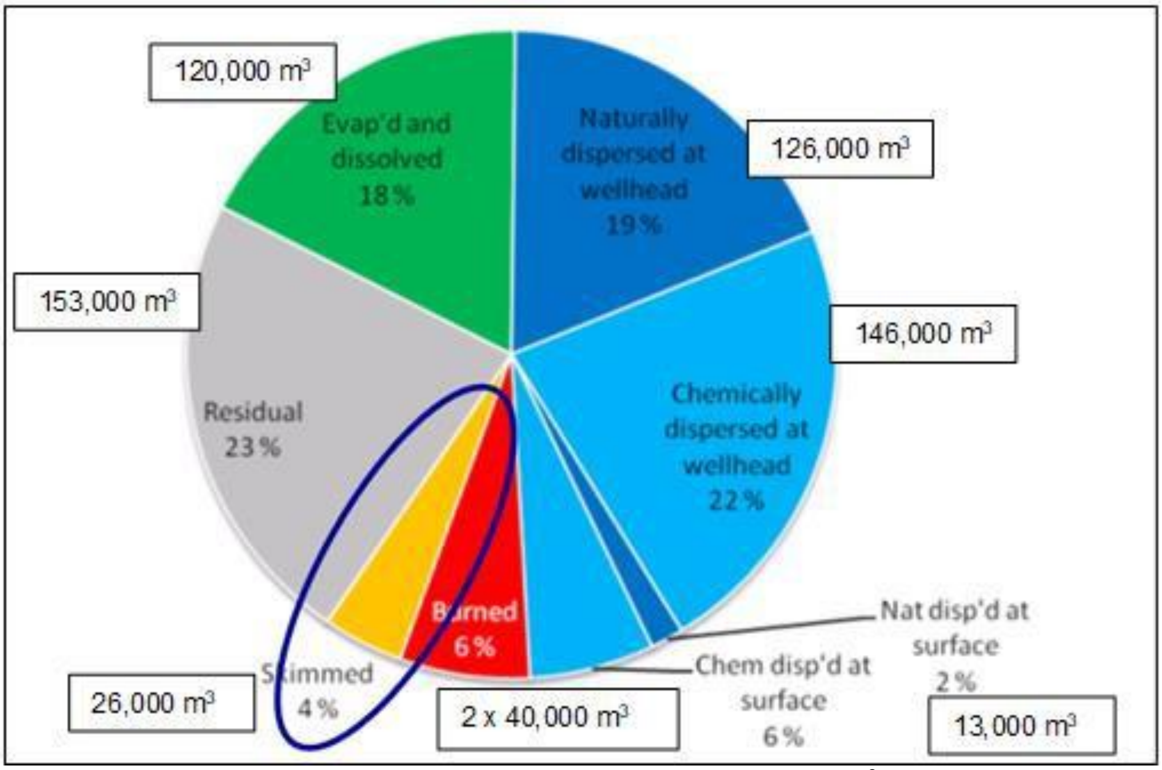


Figure 4-9 Total oil budget estimates based on an assumed amount of 665,000 m^3 oil released to the environment. (Lehr et al. 2010)

In this report, we have refined the oil budget estimates in Figure 4-9 by only estimating the assumed oil on the sea surface available for surface response by eliminating:

- Evaporated / dissolved: 120 000 m^3
- Naturally dispersed oil at well head: 126 000 m^3
- Chemically dispersed at wellhead (SSDI): 146 000 m^3
- Natural dispersed surface: 13 000 m^3

- Total 405 000 m^3

This gives 665 000 m^3 minus 405 000 = 260 000 m^3 oil residue (water-free) on the surface. By assuming an average emulsification of the oil residue with 50 % water within the first day at sea (Figure 4-8) gives a tentative volume of about 520 000 m^3 emulsion on the sea surface.

In Figure 4-10 we have therefore only considered the amount of oil residue (water-free) assumed to be available for the surface response (260 000 m^3), this gives the following surface mass balance estimate of the surface response (skimming, ISB, dispersant application).

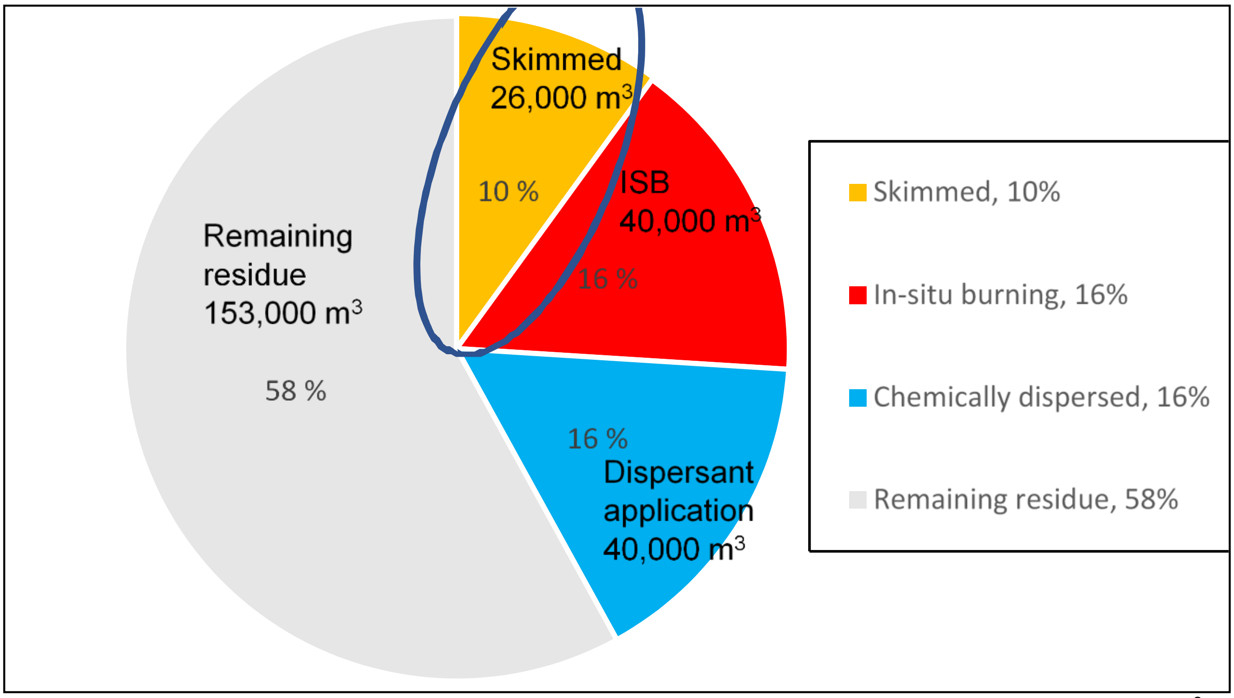


Figure 4-10 Estimated efficiency of the surface response methods relative to the assumed amount of 260,000 m^3 oil available oil / emulsion on the sea surface. released to the environment.

The "Remaining Residue" is the patchy and distributed surface oil residue that was not catched / treated by the surface response, and were exposed to long-term weathering (i.e. mousse formation, sub-merging, sinking, stranding).

4.1.6 Experiences from the field

This chapter give some examples of experiences made by mechanical recovery offshore teams during DWH-Macondo incident, this to get a better insight and understanding of some of the operational and logistical limitations and tactical priorities taken by the Incident Commanders (IC) responsible for the operating response offshore. We have made interviews with two Norwegian operational teams involved in the mechanical recovery offshore during the DWH-incident.

Anders Jørgensen, Norlense

The Norwegian company Norlense (Oil Spill Recovery - Norlense), is one of the world's leading companies for development and manufacture of Oil Spill Emergency Equipment. The Emergency Response Market products are developed for rough weather conditions. Norlense was hired directly by BP for the recovery. The company was involved in the mechanical recovery operation in the periode 9 – 20th July with four offshore boom / skimmer systems (each 300 m NO 800 boom and a Transrec 150 weir skimmers). Anders acted as "on scene advisor" for the recovery systems.

One of the systems was linked to the KC (Kevin Costner) oil-water separation system installed on the spill response vessel **Ella G** that combined the three capabilities - skimming, separation units, and storage capacity. The No-800 was operated in a "J- configuration" from Ella G (see Figure 4-11). The following is taken from the Norlense log:

- 9/7: Went out from Port Fourchon for the site. Got "stop-order" due lack permit for entering the area close to the source. Had to wait the whole day and night offshore
- 10/7: Close to the source (2-3- nm from the release drilling rig). Recovered 55 m^3 oil / water. After treatment in the KC-separator -> 4 m^3 pure oil residue
- 11/7: 70 m^3 emulsion recovered
- 12/ 7: No recovering allowed (due to weather conditions: 7 m/s wind)
- 13/7: In an area with much oil. 100 m^3 emulsion recovered in the boom within a few hours. Ready for skimming the emulsion. However, the OSC gave order to the response vessels to leave the area immediately to give priority for aerial dispersant application. Ella G had to "open" the boom and empty the 100 m^3 contained emulsion into the water again, and leave the "dispersant application zone" (frustrating for the response teams)
- 14/7: 37 m^3 emulsion recovered
- 15/7: 44 m^3 (recovered during night) + 30 m^3 emulsion recovered a in daylight (2-3 nm from release well drilling rig). Last day on-site with *Ella G*.

The seaweed in the confined emulsion reduced the flowability of the emulsion into the weir skimmer. This was partly solved by installing "chicken wires" around the skimmer (see Figure 4-11).

Most of the recovered emulsion was transported to port. Some of the emulsion was separated on board Ella G, however, the high content of seaweed in the recovered emulsion reduced the efficiency of the separator.

Figure 4-11 Upper: The No-800 was operated in a "J- configuration" from Ella G. Down: "Chicken wires" mounted around the skimmer to enhance the flowability of the emulsion into the weir**.**

- 17 / - 19. July: The other three Norlense systems was guided to an area closer to the coast, as the source had stopped leaking at that time. The intention was to recover patches of "heavy" emulsion spread over larger area by operating two 300 m booms in open U-configuration intent to lead the emulsion into another boom in J-configuration. However, low recovery efficiency was obtained, primarily because the systems were guided to areas where no oil present, or where the patchy emulsion were spread over large area.

General comments from Norlense

- The aerial guiding from spotter aircraft was in periods lacking, but also sometimes misleading as the presence of patchy area with seaweed confused the spotter-aircraft by guiding the response vessels to dense area with seaweed instead of area with oil/ emulsion.
- Much stronger restrictions for the mechanical recovery operations compared to experiences from Norwegian operations. E.g. no recovery in darkness, no operation under breaking wave conditions (> 5 m/s wind, irrespectively type of recovery systems).
- In periods there were too many recovery vessels in the same area -> "competition" between the systems
- The mechanical recovery was not given the same high priority by the "On-Scene Commander" (OSC) as for ISB and aerial dispersant application. I.e. the efficiency obtained is partly reflecting the tactical and priority decisions.

Dag Nilsen and Tor-Kristian Fagerheim, NOFI

NOFI's Oil Spill Control expertise (https://www.nofi.no/en/oilspill) has been developed over the past four decades. Their oil boom products are regarded as among the most efficient in the market. NOFI s Current Buster ® Technology has been a revolution in the oil spill contingency systems and are known for their performance in collecting oil at higher towing speeds than other boom systems.

Totally, 46 NOFI Current Buster (NCB) systems were scrambled from both Norway and oil spill response depots around the world during the response period and transported to GOM. This included both offshore systems (NCB8 and NCB4) operated from offshore vessels (single vessel or two-vessel systems, see Figure 4-4) and smaller systems (NCB2) that were operated closer to shore by e.g., fishing vessels (one-vessel systems, see Figure 4-4). The role for the NOFI personnel was primarily training of other personnel, support, and operative maintenance of the NCB systems. E.g., Tor-Kristian Fagerheim was responsible for operation and maintenance of eight of the larger systems (NCB8) that were operating offshore close to the source.

The following points were identified during the interview with NOFI:

- The amount of emulsion recovered varied highly from day to day, depending on the location to where the response systems were guided by OSC. E.g. some days, the NCB systems were guided to area with no oil.
- The IC did not allow any recovery at night, and there were restrictions to operate in waves above 1 m. Still, generally the sea was calm, with only a few days with waves above 1 m.
- Debris / seaweed was a major challenge, blocking most pumps and skimmers and often reduced the recovery efficiency (see Figure 4-11). Some skimmers, like open screw pumps performed well.
- On "good days" with presence of windrows with emulsion, two CB4 systems coupled to the OSV "Vanguard" recovered 250 m^3 emulsion on one day.
- Mud-pumps located on a separate pumping vessel were serving several NCB's, were used to empty the NCB systems when full of emulsion (30 - 60 m^3) with great success. Only small amount of free water was pumped from the NCB systems during such emptying operations.
- Several CB-systems were operating in the same area. Good communication between the CB systems. Every day, the amount recovered was reported. The recovery capacity reported from the NOFI Current Busters systems was, according to NOFI, in average 3-5 times higher than "traditional boom systems operating in the same area.

> Dag Nilsen (NOFI) who has over 40 years of operative experience from several oil spill operations in the field, claims that due to operation, oceanographic and environmental limitations (e.g. rapid spreading of the surface oil into patchy windrows, limitation of aerial guiding, reduced recovering capability at night etc), "...a realistic recovery capacity for one system will as best most likely be in the range of a few hundreds of m^3 of emulsion over a period of 24 hours, rather than the nominal recovery capacity reported in many contingency plans….".

4.1.7 Conclusions

The DWH/ Macondo incident has been the largest and the most challenging marine oil spill in the history for the petroleum industry. There are still many uncertainties both about the estimated volume of oil totally leaked out from the well at 1 500 m sea depth (assumed total to be 779 000 m^3), but also uncertainties in the quantitative efficiency numbersof the different combat operations that took place - both at the well-head on the seabed, and the response on the sea surface. In addition, there will always be uncertainties about the amount and the fate of the oil that escaped from the combat operations and ended in the marine environment. This has over the past decade opened for discussions and opinions about the eventual environmental damage of the Macondo oil spill.

In this report, we have tried to refine the official numbers of the "Oil Budget Calculator" (Lehr et. al. 2010), to give a more "fair" estimate of the efficiency of the mechanical recovery response by relating the volume recovered to the assumed amount of oil/emulsion that was available for the surface response operations. **This has been estimated to be 260 000 m^3 of the total 779 000 m^3 leaked out from the well.** Using those numbers, this gives the following calculated "efficiency" of the surface combat methods:

- Mechanical recovery 10 %
- In-situ burning (ISB) 16 %
- Surface dispersant treatment 16 %

As discussed above, there were many external environmental factors, strong internal restriction, and response priorities / tactical decisions from the Incident Commander (IC) that, according to the participating Norwegian mechanical recovery teams, which for them were frustrating as it highly influenced on the efficiency numbers. Key factors here are:

- lack of aerial guiding / misleading guiding of the recovery vessels to area with high concentrations of seaweed
- recovery operations at night were not permitted
- recovery operations in waves > 1 m (> 5m/s wind) were not permitted, irrespectively type of recovery systems
- in periods, there were too many recovery vessels in the same area à "competition” between the systems
- the mechanical recovery combat was not given the same priority by the IC as the ISB and aerial dispersant application operations. All the three surface response options (mechanical recovery, in-situ burning and dispersant application) had a potential for combat based on the oil weathering properties of the surface oil /emulsion during the first day(s). The relative efficiency numbers between these methods are therefore reflecting the response priorities and tactical decisions taken by the Incident Commander during the response operation.

4.2 Montara (2009)

4.2.1 Sources of information

The following sources have been used:

- CEDRE, 2020. Database of spill incidents and threats in waters around the world. http://wwz.cedre.fr/en/Resources/Spills.
- Dagmar Schmidt Etkin, Tim J. Nedwed, Marine Pollution Bulletin, https://doi.org/10.1016/j.marpolbul.2020.111848
- Australian Maritime Safety Authority (AMSA): https://www.amsa.gov.au/marine-environment/incidents-and-exercises/montara-well-head-platform-21-august-2009
- Report on oil characteristics: https://www.amsa.gov.au/file/2426/download?token=ZmJjQMn-
- Report of the Montara Commission of Inquiry: http://www.iadc.org/wp-content/uploads/2016/02/201011-Montara-Report.pdf

4.2.2 Description of the incident

The 21. August 2009, an uncontrolled discharge of oil and gas occurred from the Montara Wellhead mobile drilling unit. The incident occurred approximately 230 km off the north-west coast of Australia in the Montara offshore oil field in the Timor Sea (Figure 4-12). The 69 engineers and technicians on the rig were immediately evacuated unharmed to Darwin.

The released hydrocarbons were composed of:

- light crude oil (but with a wax content of up to 11 % and a pour point of up to 27 °C) rapidly forming slicks on thewater surface.
- a mixture of condensates and gas released into the atmosphere, posing an explosion risk in the vicinity of the rig.

PTTEP Australasia, the platform operator, estimated that 64 tonnes (400 barrels) of crude oil was being lost per day. It should be noted, however, that this estimate could not be confirmed at any time during the incident, nor was it possible to provide any more accurate assessment. The leak continued until 3. November 2009. An estimated total of 4 800 tonnes was then released into the sea. Response operations continued until the well was capped on 3. December 2009 (105 days). The slick created stretched up to 40 km wide by 136 km long.

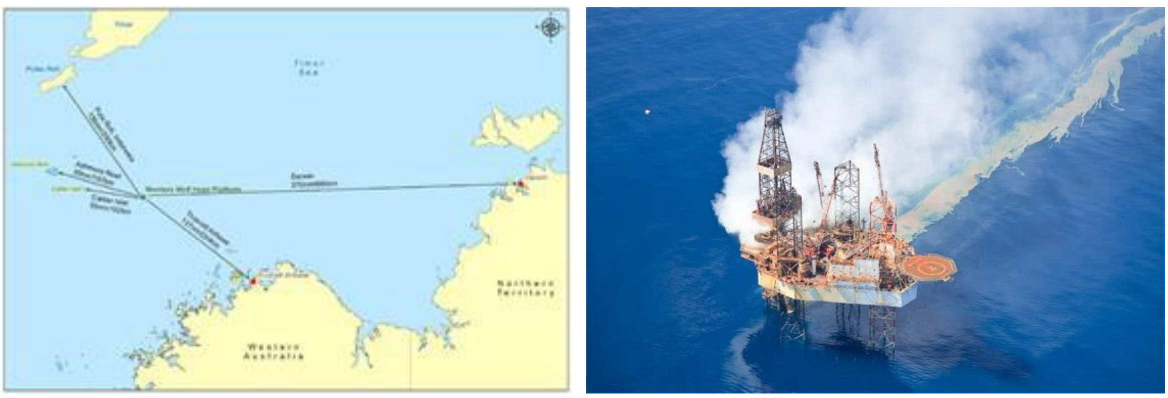


Figure 4-12 Map showing the position of the Montara platform (left) and a picture showing the oil rig and the oil slick floating away (right). The picture taken by Mark Hamilton and both images copied from: *https://www.amsa.gov.au/marine-environment/incidents-and-exercises/montara-well-head-platform-21-august-2009*

Over 130 surveillance flights were conducted throughout the duration of the operation commencing on the first day of the incident. Throughout the incident, most of the observed oil remained within 35 kilometers of the platform, with patches of sheen and weathered oil reported at various distances and in different directions as wind, temperature and currents varied. The benign conditions experienced during most of this period permitted containment and recovery operations, but to some extent also hampered the natural breakup of oil.

4.2.3 The response

Immediate response actions included:

- deploying aircraft (including a Hercules C-130 aircraft from Singapore)
- deploying AMSA personnel
- additional dispersant (initially approximately 50 tonnes) to supplement stocks at the AMSA Darwin equipmentstockpile.

AMSA's operational response was reviewed daily based on observations from morning surveillance flights. Equipment from oil industry stockpiles in Singapore and Geelong, as well as AMSA stockpiles in Darwin and other states were used in the clean-up operation. Response personnel were provided by the oil industry, AMSA and through National Response Team arrangements. This included assistance from all states and the Northern Territory. Assistance was also provided by New Zealand personnel in accordance with formal arrangements between Australia and New Zealand. In total, 247 personnel were involved in the response.

Strategy

Use of dispersants:

Dispersant spraying operations commenced on 23. August 2009 and continued until 1. November 2009:

- The Hercules C-130 sprayed a total of 12 000 liters of dispersant on 23. and 24. August.
- Aircraft contracted to AMSA as part of Australia's Fixed-Wing Aerial Dispersant Capability continued spraying operations based out of Truscott aerodrome from 25. August until 2. September, spraying 32 m^3 of dispersant.
- Vessel spraying operations were carried out from 30. August to 1. November, with 118 m^3 of dispersant sprayed.

Totally 162 m^3 of dispersants were used. Observations and sampling indicated dispersants were highly effective in assisting the natural process of degradation and minimizing the risk of oil impacts on reefs or shorelines.

Mechanical recovery:

Containment and recovery operations commenced on 5. September 2009 and continued until 30. November 2009, although no recoverable oil was located after 15. November 2009. These operations involved two vessels working together joined by a 300-meter containment boom, with a skimmer operating in the boom pocket to recover the oil. Figure 4-13 shows a picture of emulsion captured in a boom and ready for recovery by use of a skimmer.

For much of the response, two pairs of vessels undertook these operations. A total of 844 m^3 of product was recovered. It is estimated that 493 m^3 of this oil-water mixture was oil.

Table 4-2 Summary of oil spill response actions (2009).

Oil spill response	August	September	October	November	December
Hercules dispersant spraying	23.+24.				
Aircraft dispersant spraying	25	1.			
Vessel dispersant spraying	30.			1.	
Mechanical recovery		5.		30.	

Figure 4-13 Rust-colored emulsion confined in a boom ready for recovery by the skimming system. Photo: AMSA.

External factors

The conditions experienced during most of the oil spill response period were described as benign and permitted dispersing and recovery operations. The primary objective of the oil spill response was to prevent oil from reaching shore. Overall, the response to the Montara spill went well. No oil reached the shore. The closest that oil came to making landfall was recorded at 35 km from the Australian coastline and 94 km from Indonesia coastline (West Timor). Limited amounts of dispersants were applied by aircraft and boats and skimming was used to recover oil.

Internal factors

All 69 people on the West Atlas drilling rig were evacuated safely. The oil spill response was coordinated by Australian Maritime Safety Authority (AMSA) and was described as successful. A trained crew, good communication and suitable vessels proved essential for a safe and effective response. Aerial dispersant application was initiated in an early phase while mechanical recovery was put into action almost two weeks after the blowout started.

The Montara oil was quite light and combined with high sea state and air temperatures the evaporation was significant. However, the oil had a high pour point (close to ambient sea temperature) and solidified wax cakes were observed especially during periods with little sunlight (e.g. during nighttime) and for oil that had weathered for some time (increased pour point). Solidified oil was more challenging to handle both for dispersant use and mechanical recovery.

Observations made by members of the response team indicated: Along with the oil recovered there was free water. Ideally, the water could have been decanted out, but the approval wasn't granted. With limited storage on deck this was reported to slow down the progress because once the recovery tanks were full, they had to wait to have them emptied by another vessel. One of the booms used to confine the oil was damaged due to the large forces acting on it, causing a need to be going at very slow speeds when towing. Both deployment and towing vessels were large and ideally smaller vessels could have been even more useful. The heat was a big issue working on deck, on most days it was over 50 °C which made dehydration and heatstroke a major hazard. There was very limited shelter on deck. Logistically, this was a difficult spill to manage as the operations were taking place 230 km from land and so medivac and support was somewhat remote. Debris was also a problem during the recovery operations causing a problem for skimmer and hoses.

4.2.4 Recovery efficiency

The estimated amount of Montara crude oil released during the incident was 4 800 tonnes. With a density of 0.851 kg/l thisgives 5 640 m^3 of crude oil released. In the initial phase after the discharge started, application of dispersants was used as the only countermeasure. Mechanical recovery did not start until 14 days after the discharge started.

Oil type and properties

Montara oil is a waxy oil with a pour point close to that of ambient sea temperatures. The 9. September totally ten samples of oil, that had drifted on sea for some time, were analyzed onshore. The results showed that all samples were weathered with a significant loss of light (volatile) hydrocarbons. The reduction in oil volume due to evaporation for these samples was calculated to be between 4 % and 66 %, with an average of 34 %. Except for analysis of volume losses due to evaporation, we have not been able to find any other analytical data for these field samples. Fresh Montara crude oil was reported to have the following physicochemical properties:

- Density (SG): 0.851 kg/l.
- Pour point: 27 °C.
- Wax content: 11.3 %.
- Kinematic viscosity: 3.726 at 40 °C.

Descriptions of the appearance and behavior of Montara crude oil was received regularly from spill responders on site and these was supported by photographic documentation. Close to the source the oil appeared to be slowly spreading and confined to well defined slicks. As the oil was warmed (e.g., by sunlight) it exceeded its pour point, became fluid and spread more easily, forming less defined and thinned slicks. Oil contained in booms ranged from “fresh” liquid oil with a low viscosity and brown colour to lighter-coloured oils, possibly emulsions. The fresh oil was recovered well by the deployed skimmers and reportedly contained little water. The emulsions observed ranged in appearance, possibly reflecting the degree of emulsification, but possibly also reflecting a variable wax content. The separation of waxes from the oil was evident and wax "cakes" were observed.

Mass balance / oil budget

The SINTEF Oil Weathering Model (OWM) has been used to predict weathering properties for the Montara crude oil, including mass balance without any recovery data included. Very few analytical data are found for the Montara oil and the OWM was set up with two options:

Option 1: A boiling point curve was prepared for the fresh Montara crude oil based on a simulated distillation profile presented in the oil characteristics report prepared for AMSA. This was combined with the few physicochemical data given above.

Option 2: The boiling point curve and the physicochemical data for Montara were compared with many crude oils in the OWM database and matched quite well with a Norwegian crude oil. This crude oil was then used as a "model oil" and predictions prepared based on this oil.

The following input data were used:

- 4 800 tons of Montara crude oil released over 10 weeks (70 days) – 21. August to 3. November 2008.
- Sea water temperature 28 °C.
- Wind: 2, 5, 10 and 15 m/s.
- Water uptake: 42 %.

The predictions at 5 m/s wind were similar for the two options above. At 10 m/s wind, option 1 gave a very high natural dispersion of 42 % (after 24 hours weathering time) versus 28 % for option 2. The option using the Norwegian crude oil (option 2) as a "model oil" was selected for further calculations in this report.

Figure 4-14 presents the predicted mass balance at 5 and 10 m/s wind for option 2. The weather conditions were described as benign most of the period during the oil spill, but since the oil recovery actions were ongoing for a period of more than 70 days varying wind conditions should be expected. The mechanical recovery was probably ongoing at different distances from the release point (the rig). As an average it is assumed that it took place at a distance corresponding to 24 hours drifting time from the source, which is used in the further calculations.

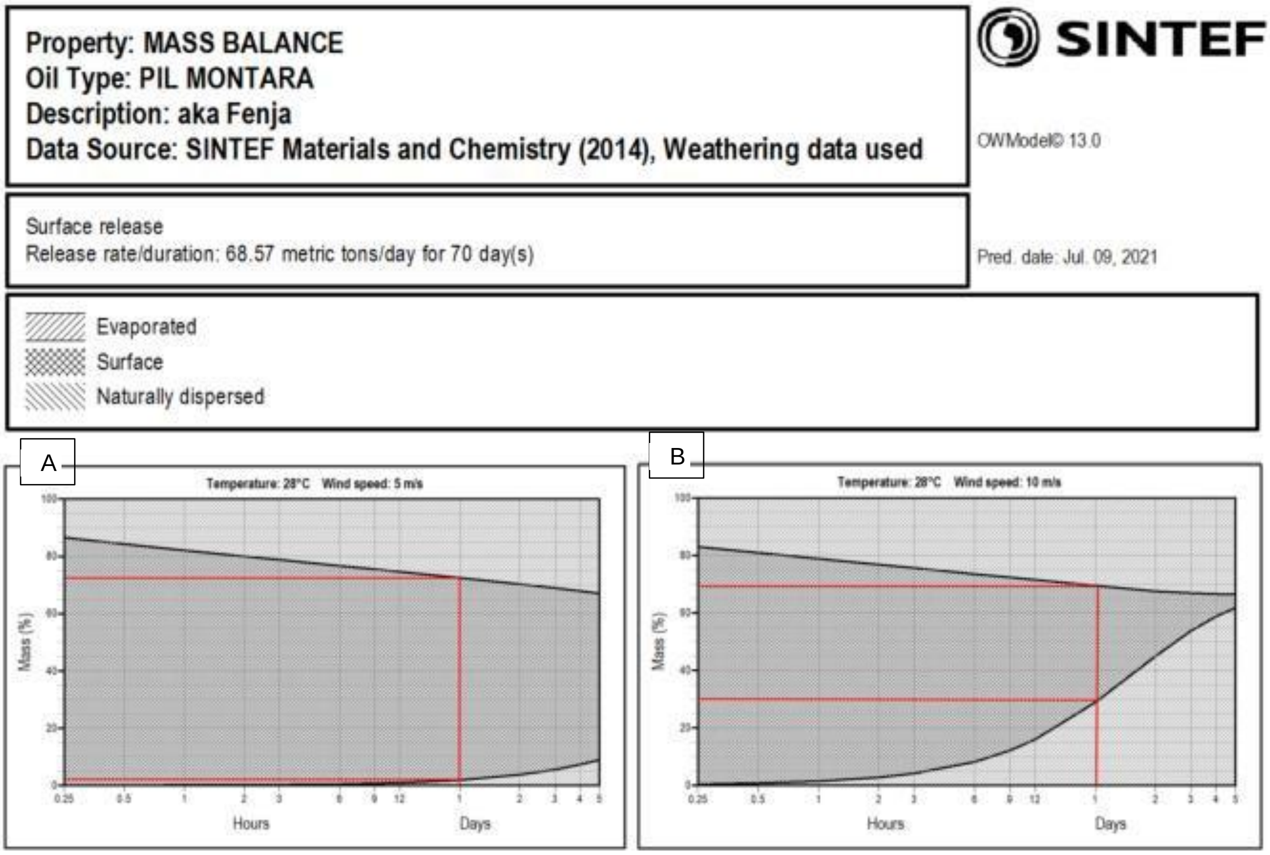


Figure 4-14 Predicted mass balance of Montara crude oil at 28 °C sea temperature and 5 m/s wind (A) and 10 m/s wind (B), using a Norwegian crude oil as "model oil".

Mass balance including oil spill response options and estimation of efficiency

We have not found any real wind file for this incident. It was reported that benign conditions were experienced during most of the period. However, during the 75 days of oil spill response operations it should be expected that the wind conditions varied from very calm conditions (5 m/s wind or less) to rougher conditions (10 m/s wind or more). As a rule of thumb, at 5 m/s wind breaking waves (white caps) starts to appear at sea offshore. This is a premise for natural dispersion of oil which normally increases with increasing wind speed. Table 4-3 gives input and assumptions used as a basis for estimation of the efficiency of the mechanical oil recovery actions during the incident:

Table 4-3 Input and assumptions for the mass balance calculations for Montara

Incident/activity	Comments
Oil release: 21/8–3/11, 2009	4 800 tonnes of Montara crude oil was released over a period of approximately 75 days.This gives: 5 640 m^3, based on density: 0.851 kg/l. The crude is described as a light oil, but with high wax content and pour point.
Use of dispersants	23/8-24/8: 12 m^3 dispersant (Hercules) 25/8-02/9: 32 m^3 dispersant (Aircraft) 30/8-1/11: 118 m^3 dispersant (Vessel) Totally: 162 m^3 dispersant applied
Oil dispersed	Assumes a DOR (Dispersant-to-Oil Ratio) of 1:10 (gives: 1 m^3 of dispersant disperses 10 m^3 of oil): • 162 m^3 dispersant used x 10 = 1 620 m^3 oil residue dispersed.
Mechanical recovery	05/9-15/11: Two pairs of vessels participated.

<table>
<tr><td></td><td>Totally 844 m^3 of product (oil-water mixture) was recovered. Estimated that 493 m^3 of this was oil residue.
Based on these estimations: If the total product recovered contained only emulsion (no free water) the water content in the emulsion would be 42%.</td></tr>
<tr><td>Total mass balance at 5 and 10 m/s wind.
All parameters included.</td><td>Assumptions:
• Both use of dispersants and mechanical recovery performed at a distance from the source corresponding to 24 hours drifting time.
• Assumes an average sea temperature of 28°C.

Table showing the amount of oil (calculated as water free oil) being dispersed or recovered as a percentage of the oil released, evaporation and natural dispersion included:

<table>
<tr><th></th><th>5 m/s wind (Figure 4.2.4A)</th><th>10 m/s wind (Figure 4.2.4B)</th></tr>
<tr><td>Evaporated</td><td>28% (1 579 m^3)</td><td>32% (1 805 m^3)</td></tr>
<tr><td>Naturally dispersed</td><td>3% (169 m^3)</td><td>28% (1 579 m^3)</td></tr>
<tr><td>Chemically dispersed</td><td>29% (1 620 m^3)</td><td>29% (1 620 m^3)</td></tr>
<tr><td>Mechanical recovery</td><td>9% (490 m^3)</td><td>9% (490 m^3)</td></tr>
<tr><td>Residual oil</td><td>31% (1 782 m^3)</td><td>2% (146 m^3)</td></tr>
</table></td></tr>
<tr><td>Surface oil mass balance at 5 and 10 m/s wind.
Only oil available for oil spill response measures.</td><td>Assumptions:
• Both use of dispersants and mechanical recovery performed at a distance from the source corresponding to 24 hours drifting time.
• Assumes an average sea temperature of 28°C.

Table showing the amount of oil (calculated as water free oil) being dispersed or recovered as a percentage of the oil available on the surface, evaporation and natural dispersion deducted:

<table>
<tr><th></th><th>5 m/s wind (Figure 4.2.5A)</th><th>10 m/s wind (Figure 4.2.5B)</th></tr>
<tr><td>Chemically dispersed</td><td>41% (1620 m^3)</td><td>72% (1 620 m^3)</td></tr>
<tr><td>Mechanical recovery</td><td>13% (490 m^3)</td><td>22% (490 m^3)</td></tr>
<tr><td>Residual oil</td><td>46% (1 782 m^3)</td><td>6% (146 m^3)</td></tr>
</table></td></tr>
</table>

As can be seen from the mass balances presented in Figure 4-15 and Figure 4-16 there is a large difference in predicted natural dispersion between the two wind speeds simulated. Looking at the total mass balance, as in Figure 4-14, the amount of oil being chemically dispersed and mechanically recovered as a percentage of the total oil release is the same regardless of wind speed. The main difference is increased natural dispersion and less calculated residual surface oil at increasing wind speed. The amount of oil being recovered mechanically is estimated to constitute 9 % of the totally released oil (5 640 m3).

If we look at the oil that is predicted to be available at the surface after 24 hours at 5 and 10 m/s wind (Figure 4-14), the amount of oil being recovered mechanically is estimated to be between 13 % to 22 % depending on the wind conditions (Figure 4-16).

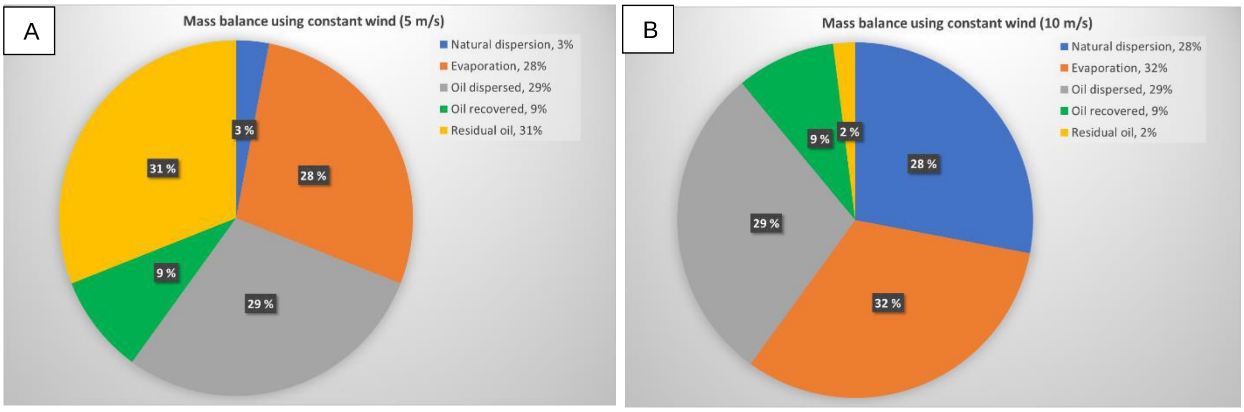


Figure 4-15 Mass balance including dispersed and recovered oil at 5 m/s (A) and 10 m/s (B) wind.

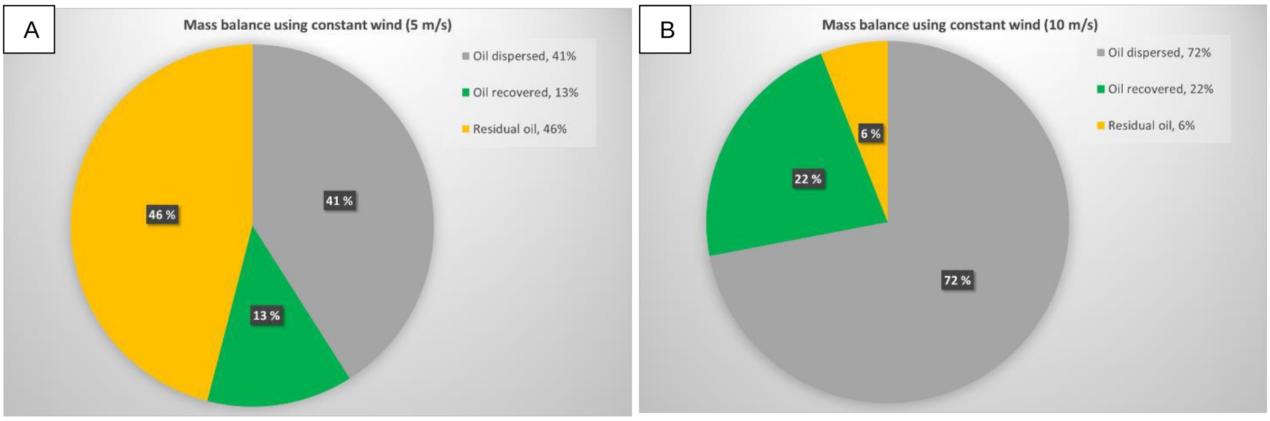


Figure 4-16 Mass balance of surface oil including dispersed and recovered oil at 5 m/s (A) and 10 m/s (B) wind.

4.2.5 Conclusions

490 m^3 of the 5 640 m^3 oil released was recovered mechanically during this incident. This constitutes approximately 9 % of the oil release. After 24 hours drifting time approximately 31 % of the oil would have been lost to evaporation and natural dispersion at 5 m/s wind, while at 10 m/s wind the loss would have been up to 60 % according to predictions by use of the SINTEF OWM. Taking this into consideration the efficiency of mechanical recovery would have been between 13 % (at 5 m/s wind) to 22 % (at 10 m/s wind) calculated on the amount of oil available on the sea surface.

Dispersants were used in an early phase of this incident and mechanical recovery was initiated almost 2 weeks after the spill started. The resources used were two pairs of recovery systems. It is difficult to say whether mechanical recovery would have been more efficient if it had been started earlier and if more systems had been invoiced. This was a blow out with limited amounts of oil being released per day, so it is reason to believe that more systems would have given limited additional recovery. However, there was a "competition" between use of dispersants and mechanical recovery and if dispersants had not been used the amount of oil recovered mechanically, and hence the efficiency, would probably have been higher.

4.3 Draugen (2003)

4.3.1 Sources of information

There are a few sources discussing the oil spill response actions for this incident, and the information about total amount of oil spilled and the amount of oil recovered seem to be consistent between the different sources. The following sources have been used:

- The Norwegian Environmental Agency: https://nettarkiv.miljodirektoratet.no/hoeringer/tema.miljodirektoratet.no/no/Nyheter/Nyheter/Old-klif/2003/November/Anmelder_Norske_Shell_ASA_for_oljeutslipp/index.html
- The Norwegian Petroleum Museum: https://draugen.industriminne.no/nb/2018/05/25/det-tredje-storste-oljeutslippet/
- From newspaper: https://www.aftenbladet.no/okonomi/i/dqKBB/sprekk-og-uklare-rutiner-ga-oljeutslipp-paa-draugen
- Per S. Daling, Merete Øverli Moldestad, Frode Leirvik (SINTEF Kjemi) og Arne Follestad (NINA) (2003): "Oljeutslipp på Draugen mai, 2003 – Fysikalsk-kjemisk karakterisering av oljeflak og vannmasser, samt fugleobservasjoner, 23. mai 2003." SINTEF Rapport STF66 F03052.
- Frode Leirvik (2008): "Draugen – Egenskaper og forvitring på sjøen relatert til beredskap". SINTEF Rapport A5637.
- The Norwegian Coastal Administration: A large number of documents from NCA's archives including daily Action plans.
- The Norwegian Petroleum Directorate: "Granskningsrapport etter hendelse knyttet til oljeforurensning på Draugenfeltet 19.5.2003".

4.3.2 Description of the incident

At approximately 23.00 o'clock Monday 19. May 2003 considerable amounts of oil was visually observed at sea from the Draugen platform. Ongoing loading on site and the oil production was immediately shut down and an emergency organization was established both at Draugen and on Shell's emergency central in Kristiansund. The reason for the leakage proved to be cracking in an 12" end coupling at the Garn Vest manifold on the sea floor pipeline built to transfer the oil to Draugen. The distance to Draugen was 3 km. An oil slick of approximately one nautical mile in circumference was discovered the same evening. Figure 4-17 shows a snapshot of the situation during the release 19. May, based on images from SAR helicopter. It was estimated that 750 m^3 of Draugen crude oil was released to sea during the incident.

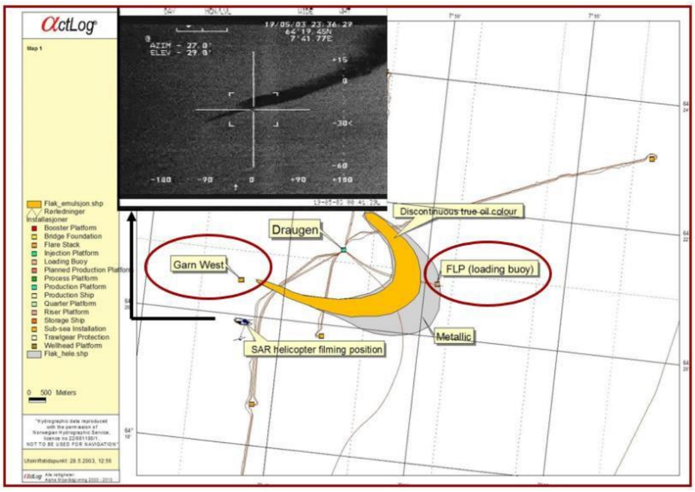


Figure 4-17 Snapshot of the situation during the release 19th May, based on images from SAR helicopter.

4.3.3 The response

Oil recovery was initiated about 12 hours after the leakage was discovered, by the OR vessel "Skandi Stord". Table 4-4 gives an overview of the main oil spill response activities reported during the Draugen spill.

Table 4-4 Main activities related to oil spill response for the Draugen 2003 spill.

Date	Time	Activity
19. May	23.00	The release was discovered.
20. May	10.50	Oil recovery was initiated by "Skandi Stord" assisted by "Ocean Fighter". "Skandi Stord" initially judged the oil slick to be favorable for mechanical recovery.
20. May	21.30	Oil recovery was terminated due to scattered small oil slicks with low thickness. Approximately 580 m^3 of a mixture of emulsion and water was recovered.
21. May		No or very little recovery. "Skandi Stord" was used to try to disperse the oil mechanically by use of the bow wave. Use of dispersants was evaluated but was not recommended due to environmental conditions. Mechanical dispersing proved to have little effect as documented by aircraft (LN-SFT).
22. May		OR vessels were searching for oil and continued with oil recovery where possible. The oil spread over large areas before the slick thinned out and was split into smaller slicks which eventually disintegrated.
23. May		Mechanical recovery from "Skandi Stord" commenced after midnight 23. May, concentrating on thicker "fingers" in the slick. "Skandi Stolmen" was mobilized and had booms in the water at 12.15. Sampling from the oil slicks and measurements of oil concentrations in the upper water column was performed by SINTEF.
26. May		Oil recovery was no longer possible, and the recovery operations were finalized. In addition to "Skandi Stord", "Skandi Stolmen" was used in the recovery operations. Totally, 1 200 m^3 emulsion/water was recovered and the amount of pure oil was calculated to 176 m^3.

The wind conditions were favorable for mechanical recovery the first three days before the wind increased on the 23. May to between 10 to 13 m/s and stayed high until the oil recovery was terminated on the 26. May. Figure 4-18 shows the measured wind from 19. May (at 18:00) to 24. May (at 10:00) with 3 hours intervals. Some readings are missing for a period of 24 hours from late in the day of 21. May, but the wind conditions were reported to be calm.

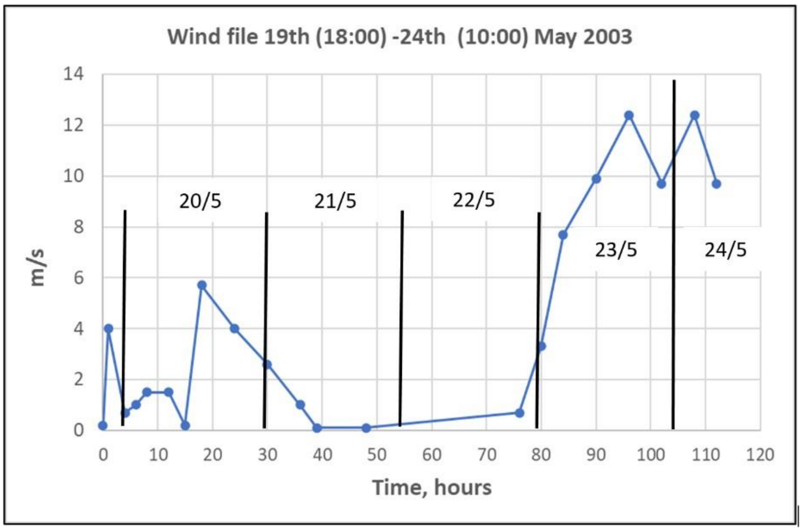


Figure 4-18 Wind file from 19. May until 24. May 2003 at the Draugen oil field.

Strategy

The main strategy was to use mechanical recovery. Use of dispersants was evaluated but was not recommended due to environmental conditions (e.g., fish larvae in the area). Besides, investigation of the incident revealed that the equipment used for dispersion was not operational. Mechanical dispersing was tried allowing a vessel to travel through the slick at high speed, but it proved to have little effect. The following mechanical recovery actions were performed:

- The OR vessel "Skandi Stord" equipped with NOFO boom and Transrec skimmer system started with mechanical recovery 12 hours after the spill was discovered. During this first mechanical recovery action, lasting from 10:50 until 21:30 on the 20. May, approximately 580 m^3 of a mixture of emulsion and water was recovered.
- A second OR vessel, "Skandi Stolmen", was mobilized and participated in the second oil recovery action, together with "Skandi Stord", from the 23. May until further mechanical recovery was finalized 26. May. It was reported that approximately 620 m^3 of emulsion and water was recovered during this action, giving totally 1200 m^3 of emulsion and water recovered during the entire recovery actions.

Figure 4-19 shows a picture of emulsion confined in the boom by "Skandi Stord". Experience from the recovery operations showed that the Transrec system pumped a lot of free water. The viscosity of the emulsion was measured to 4 400 – 10 000 cP (measured at a shear rate of 10 s-1 and a temperature of 10 – 12 °C) after 3-4 days at sea. It was reported that a dosage of more than 1 000 ppm of emulsion breaker (Alcopol) was necessary to break the emulsion. There were problems with emptying the tanks with recovered emulsion from the OR vessel.

Figure 4-19 Emulsion confined in a boom ready for recovery by the Transrec system onboard "Skandi Stord."

External factors

The wind conditions during the period when oil spill response was performed (approximately one week) are shown in figure 4.18. The first days it was reported low winds and a significant wave height below 0.7 m. It has been reported that it was fog in the area from the 20. May until the 23. May, with low winds. This cannot be verified in the daily action reports during the incident. At day 3 (May 23.) the oil had drifted closer to the Froan area (Figure 4-20). The oil had then formed a high-viscous and stable water-in-oil (w/o) emulsion and was spread over large areas. Observations from the LN-SFT aircraft (from approximately 1 000 feet) on the 24. May documented the patchiness of the oil slick (Figure 4.4.5). The picture with patches of orange/reddish emulsion in Figure 4-20 may indicate that the wind speed was above 5 m/s which is regarded as the lower wind speed when one starts to see breaking waves (white caps).

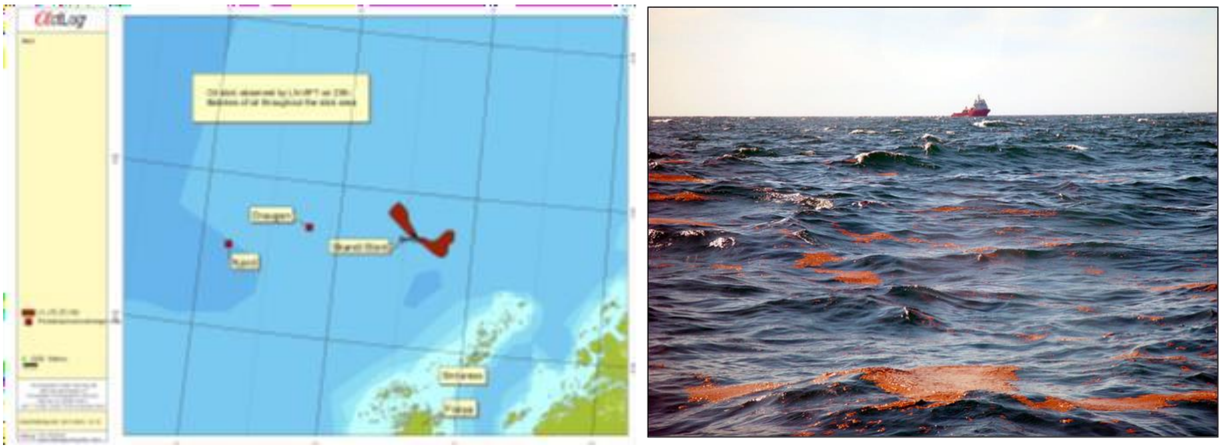


Figure 4-20 After 3 days (May 23.) the oil had drifted towards east and was spread over large areas with patches of orange/reddish emulsion.


Figure 4-21 Observations from LN-SFT 24. May 2003. The left picture show patches of emulsion 1-5 m in diameter surrounded by sheen. The right picture shows an area with larger patches, 50 -100 m long).

Internal factors

A report of inquiry of the incident prepared by the Norwegian Petroleum Directorate state that:

- "Skandi Stord" was mobilized 1 hour and 50 minutes after it was visually confirmed that it was oil on the surface.
- Oil recovery started 12 hours after the oil spill was discovered.
- SAR-helicopter with IR camera was used at an early stage to monitor the oil, but due to technical problems, no monitoring of the oil was done from midnight until 07:30 on the morning of 20. May.
- The equipment used for dispersion was not operational and chemical dispersion could not be performed.

4.3.4 Recovery efficiency

The estimated amount of Draugen crude oil released during this incident was 750 m^3. This amount is consistent between several literature sources. It was reported that a total of 1 200 m^3 of a mixture of free water and emulsion was recovered. We have not been able to find any estimates of how much of this was free water and how much was emulsion. However, it is reported that a total of 176 m^3 of water free oil (water content in the emulsion deducted) was taken ashore from the recovery operations.

Oil type and properties

As a basis for this evaluation, we have used predictions from a weathering study of crude oil from Draugen block 6407/9 performed in 2008 (SINTEF report A5637). It is assumed that these data are relevant for the oil spilt during the 2003 incident. Table 4-5 gives some physicochemical data for the Draugen crude oil.

Table 4-5 Physiochemical data for the Draugen oil based on a weathering study at SINTEF.

Oljetype	Residue	Fordampet (vol.%)	Residue (vekt %)	Tetthet (g/mL)	Flammepunkt (°C)	Stivnepunkt (°C)	Viskositet 13°C (mPas)	Viskositet 5°C (mPas)
Draugen	Fersk	0	100	0,823	-	-24	6	11
	150°C+	30,1	74,2	0,875	49	3	54	161
	200°C+	40,9	63,9	0,890	96	12	284	843
	250°C+	52,9	51,8	0,904	137	18	1490	5890

SINTEF was mobilized offshore for oil sampling and analysis and based on the SINTEF field report: "Oljeutslipp på Draugen mai, 2003 – Fysikalsk-kjemisk karakterisering av oljeflak og vannmasser, samt fugleobservasjoner, 23. mai 2003", the following data were reported based on sampling and analysis of totally 4 surface oil samples:

- The sea water temperature was measured to approximately 9°C.
- The water content in the emulsion was measured to 55 – 62 % (sampled and measured the 23. May).
- The viscosity was measured to 4 400 – 10 000 cP at shear 10 s-1 and 10 – 12 °C (sampled and measured the 23. May).
- Based on analyses by use of GC-FID the evaporation was calculated to approximately 50 % (sampled andmeasured the 23. May)

Mass balance / oil budget

The SINTEF Oil Weathering Model (OWM) has been used to predict weathering properties for the Draugen crude, including mass balance without any recovery data included. Two sets of predictions have been prepared, one using constant wind (2, 5, 10 and 15 m/s) during the entire simulation period (5 days) and one using real wind speeds as measured during the incident. Figure 4-22A shows the predicted mass balance using 5 m/s wind and figure 4-22B using the real wind readings. The first mechanical recovery action started 12 hours after the release was discovered and lasted for approximately 12 hours, as indicated in the two figures. The second recover action started approximately 3 days after the release was discovered (May 23.). This is also indicated in the two predictions by the third red vertical line.

In the constant wind prediction at 5 m/s wind (Figure 4-22), the evaporation in the first recovery action is predicted to be between 38 to 42 % and the natural dispersion between 3 to 4 %. At the starting point of the second recovery action the evaporation is predicted to be 48 % and the natural dispersion 6 %.

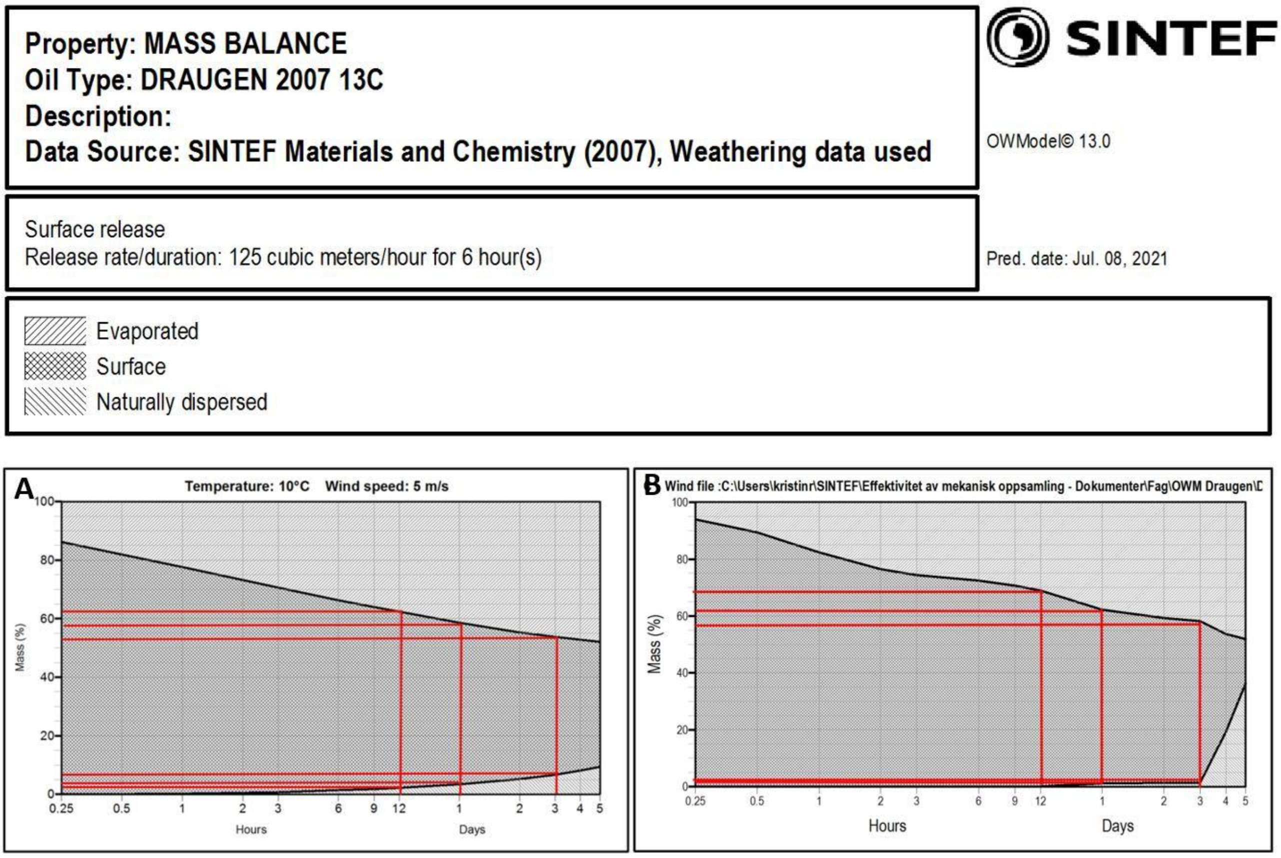


Figure 4-22 Predicted mass balance of Draugen crude oil at 10°C sea temperature and 5 m/s wind (A) and by use of real wind readings during the incident (wind file in figure 1.2) (B).

For the real wind prediction (Figure 4-22B), both evaporation and natural dispersion is slightly lower and for the first recovery action it is predicted to be between 32 to 38% and the natural dispersion between 0 to 2 %. At the starting pointof the second recovery action the evaporation is predicted to be 43 % and the natural dispersion 3 %. Analysis of samples taken at the start of the second recovery action (see above) indicate an evaporation of approximately 50 %.

Mass balance including recovery and estimation of efficiency

Table 4-6 gives an overview of inputs/assumptions used as a basis for estimation of the efficiency of the mechanical oil recovery operations during the Draugen spill.

Table 4-6 Input and assumptions for the mass balance calculations for Draugen.

Parameter	Comments
Oil released 19/5 2003	750 m^3 of Draugen crude oil was spilt over a period of 6 hours.
1. recovery action, 20. May	580 m^3 of a mixture of free water and emulsion was recovered over a period of 12 hours.
2. recovery action, 23. May	620 m^3 of a mixture of free water and emulsion was recovered over a period of 2-3 days.
Oil recovery	It was reported that 176 m^3 of water free oil was taken onshore. This is approximately 15 % ofthe 1 200 m^3 mixture of free water and emulsion that was recovered during the mechanical recovery actions. There is no information on how much water free oil was recovered in each of the two recovery actions. The water free oil recovered constitutes approximately 23 % of the crude oil that was originally spilt.

Mass balance at 5 m/s wind	Figure 4-22A and B show a difference in mass balance between the 1. and 2. recovery action. For simplicity, the mass balance predicted at day 3 (start of the 2. recovery action) have been used to prepare a mass balance including the oil recovered. From Figure 4-22A: Evaporated: 48 % (360 m^3 of water free oil) Naturally dispersed: 6 % (45 m^3 of water free oil)Recovered: 23 % (176 m^3 of water free oil) Calculated: Residual oil: 23 % (169 m^3 of water free oil)
Mass balance at measured wind	From Figure 4-22B: Evaporated: 44% (323 m^3 of water free oil) Naturally dispersed: 3 % (23 m^3 of water free oil)Recovered: 23 % (176 m^3 of water free oil) Calculated: Residual oil: 30 % (228 m^3 of water free oil)

Figure 4-23A shows the predicted mass balance at constant wind of 5 m/s, with recovered oil included. Residual oil is the difference between the amount of oil released and the parameters that can be calculated from the predictions (evaporation and natural dispersion) plus the recovered oil. Probably, it consists mainly of oil remaining on the surface that has been split into smaller slicks or patches and spread over larger areas and as such difficult to access. Assuming the amount of oil denoted as residual oil is on the surface, approximately 50 % of the available surface oil was recoveredmechanically.

For the predicted mass balance using the real wind file (Figure 4-23B) both the evaporation and natural dispersion was lower than for the 5 m/s wind predictions. Because the amount of oil recovered was the same, the residual oil increases somewhat. This means that the amount of available surface oil recovered decreases to 44 %. However, the difference between these two wind scenarios is probably very small.

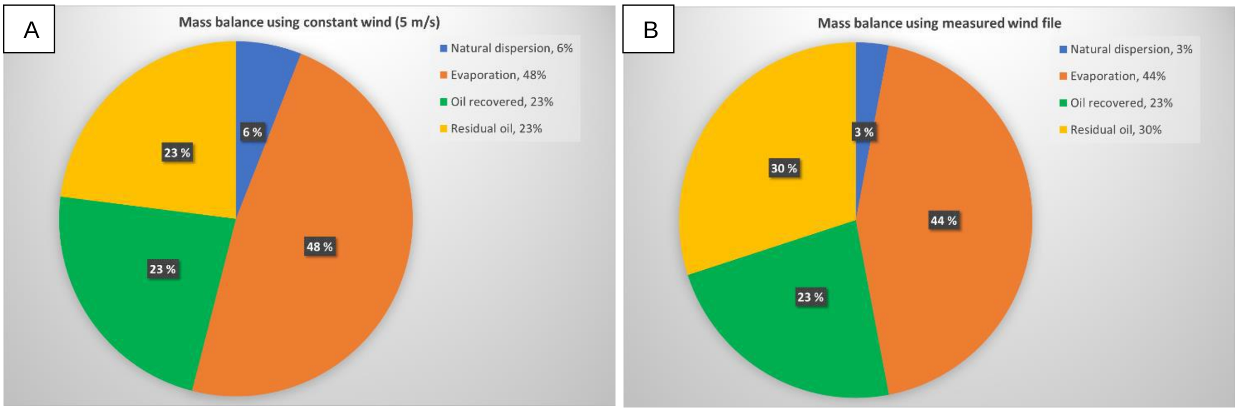


Figure 4-23 Mass balance including recovered oil using constant wind of 5 m/s (A) and wind measured during the incident (B).

4.3.5 Conclusions

Even if there are uncertainties about key figures from the Draugen 2003 oil spill there seems to be consistency between different information sources. It was estimated that 750 m^3 of Draugen crude oil was released over a period of a few hours. Approximately 1 200 m^3 of a mixture of emulsion and free water was recovered mechanically through two recovery actions separated in time. Approximately 176 m^3 of water free oil was taken ashore after the recovery actions. The weathering of the oil and the mass balance was different between the two recovery actions, but the information available does not support any detailed calculation for each of the actions. Therefore, we have used input data on day 3 (start of the 2. recovery action) as a basis for the mass balance calculations.

If we subtract the amount of surface oil that evaporated and dispersed naturally it seems that approximately 50 % of the oil available on the surface was recovered. The remaining 50 % surface oil is referred to as residual oil and consisted mainly of oil spread over larger areas as patches. This is supported by pictures taken during the incident. Also, from day 3 the wind increased and seemed to remain relatively high towards the end of the second recovery action. Then the natural dispersion increased due to wave action and in the mass balances presented in figure 1.7 natural dispersion may be underestimated.

The mechanical recovery operations may possibly have been even more efficient if:

- The oil recovery had been initiated earlier than what was performed (<12 hours after the oil spill was discovered). The weather conditions were optimal for mechanical recovery the first days.
- More than one mechanical recovery system had been mobilized in an early phase.
- More continuous remote sensing from aircraft had been performed.
- The recovery action could have continued between the evening of 20th of May and the morning of 23rd of May, where it according to available information do not seem to have been carried out any mechanical recovery.

As has been reported orally it was fog in the area for the first 3 days after the spill. This cannot be verified in written documentation, but if this is correct it can have caused problems both for remote sensing of the oil slick and mechanical recovery.

4.4 Godafoss (2011)

4.4.1 Sources of information

The information in this chapter is based on the following sources:

- NCA, 2014. Godafoss response evaluation report from the Norwegian Coastal Administration ("Evaluering av aksjon Godafoss").
- NCA 2011A. Post spill evaluations – se going units.(" Operative erfaringer etter aksjon Godafoss - et sammendrag basert på alle sjøgående enheters evalueringer, Notat from Trond Hjort-Larsen, 22.3.2011
- "Oil spill response in 20 degrees minus" – presentation from NCA (NCA, undated)
- NCA 2011B. Oil budget report from the Norwegian Coastal Administration "Oljeregnskap". Torunn Østmann. NCA 14.10.2011.
- SINTEF, 2011. Oil characterization report ("A20243 Åpen Rapport. Godafoss. Karakterisering av oljeprøver, naturlige prosesser og mulige tiltaksalternativer"). SINTEF Materialer og Kjemi 2011-09-05.
- Personal communication with NCA personnel involved in the response

4.4.2 Description of the incident

The 17th of February 2011, the container vessel Godafoss was on its way out of the town of Fredrikstad when it grounded on the Kvernskjær-reef in the Hvaler archipelago (Figure 4-24 and Figure 4-25). The vessel was loaded with 439 containers and had 555,5 m^3 heavy fuel oil (IFO 380) on board.

At 20:00, Horten VTS received a report of the grounding. The vessel suffered extensive damage to the underside of the hull, and four oil tanks were damaged/penetrated. 112 cubic metres of heavy oil quickly flowed into the sea. Efforts were made extensively at sea and along land to limit the harmful effects of the discharge. In parallel of the on sea-response, remaining oil in the ruptured tanks were pumped out. The on-sea recovery ended 28.02 when Godafoss went out of Norwegian waters to Denmark for repairs.

The response entered a beach cleaning phase through 2011 and finalized in the summer of 2012.

Figure 4-24 Godafoss after the grounding. Photo: NCA.

4.4.3 The response

Strategy

The Norwegian Coastal Administration initiated a Governmental response at midnight on 18.02.2011. A significant response was mobilized by NCA, including Coast Guard, NCA OR vessel, Swedish vessels, and municipal response resources. The response was also supported with remote sensing from NCAs surveillance plane. Initial inclusion booming around the vessel was the initial measure to reduce spreading of oil, after that open water recovery as well as recovery in ice.

The resources involved in mechanical recovery at sea were:

- CGV “Harstad” + TW Balder (NOFI 800 S boom)
- CGV “Nornen” (NO 450 S boom and grab-collector
- OV 01 oil spill vessel
- OV 03 Oil spill vessel (Sandvik conveyer belt)
- KBV 001 Poseidon (Lamor Side Collector (LSC), Lamour brush belt skimmer, Heat capacity on board
- KBV 051 Skiy (Built in, advancing system with collector arms, Free-floating skimmer, ORO tank 190 m^3
- Ingeborg Platau

External factors

The response was carried out in very cold weather conditions. A high-pressure system over southern Scandinavia led to low temperatures as low as minus 20 °C. The Oslo fjord froze out to the Færder island. Difficult conditions with sea ice in the fjord around the vessel made it difficult to estimate the size of the spill. Due to low winds, the spreading of the oil was mainly driven by sea currents. Initially, the oil moved in narrow strips in the current into the Oslo fjord, and then towards Vestfold coast and down past Telemark and Agder counties. Oil was found on land as far south as Lindesnes. The cold made it very thick and easy to collect at sea and on land. When it got milder, the oil became more thin-flowing and harder to collect.

Figure 4-25 Godafoss grounding position. (Photo: NCA)

Internal factors

According to NCAs post-spill evaluation the main positive experiences from the response at sea were:

- A very large proportion of the oil spill (approx. 50 %) was recovered at sea. An important reason for this wasKBV 001 and KV Harstad's equipment for detecting the oil in the dark.
- The cooperation with the Swedish Küstbevakningen worked very well. The combination of Swedish and Norwegian large and small units with varying degrees of mobility, flexibility and operational areas demonstrated the importance of having available a range of different resources in the response.
- The use of Swedish and Norwegian surveillance aircraft, helicopters and AIS buoys gave a good picture of the operation and spreading of the oil.
- It was important that the Swedish vessels were better equipped with systems that could handle oil mixed with ice. They had melting capacity that melted the ice, and access to heat that could loosen frozen couplings and more.

According to NCA the most important strategic and tactical improvement points from the response were:

- Rapid inclusion booming around the ship was delayed and effected by sea ice. KBV 050 had booms on site Friday 17.02.05:00, (Expandi 4300) that could have been used, but for some reason inclusion booming was not fully installed around the ship until several hours later with booms arriving from NCAs depot. This caused some leakage of oil.
- Some communication challenges, especially from aircraft to the vessels were noted.
- The damaged ship was dragged off the reef while most of the of the oil spill resources (KV Nornen, Harstad, buster systems,etc.) were still en route to the Østfold coast after assignments on the Vestfold side.
- There were limited skimmer resources (both in number and type) that handled the very viscous oil (see Figure 4-26), which led to a reduced recovery for a period. Only KV Nornen was equipped with a grab. This resulted in a lot of transport back and forth for KV Nornen to unload oil, which meant that SOSC (task force leader sea that was KV Nornen) was sometimes unavailable on the scene. The lack of presence led to some communication challenges.
- More resources in operation off Kragerø on 20 February could have resulted in larger quantities of oil accumulated.
- The escort of "Godafoss" from to Denmark was done too late in the day, and at too high speed through the water in the first phase, and with a lack of active oil spill recovery equipment.
- Oil sticking on the outside hull should have been removed before the tow went off. It was later assumed that this oil polluted Swedish waters during the tow - estimated to 5 tonnes.

According to NCAs post-spill evaluation the main positive experiences from the response at sea were:

- A large proportion of the oil spill (approx. 50 % initially reported) was recovered at sea. An important reason forthis was KBV 001 and KV Harstad’s equipment for detecting the oil in the dark.
- The cooperation with the Swedish Küstbevakningen worked very well. The combination of Swedish and Norwegian large and small units with varying degrees of mobility, flexibility and operational areas demonstrated the importance of having available a range of different resources in the response.
- The use of Swedish and Norwegian surveillance aircraft, helicopters and AIS buoys gave a good picture of the operation and spreading of the oil.

- It was important that the Swedish vessels were better equipped with systems that could handle oil mixed with ice. They had melting capacity that melted the ice, and access to heat that could loosen frozen couplings and more.

NCAs initial reports of recovered fluids delivered from the vessels involved in the recovery operations is presented in Table 4-7.

Table 4-7 Reported delivered oil from vessels (NCA).

Dato	Tatt opp	Levert	Akkumulert	Kommentar
18.02	KBV 050 6 m3			
19.02		KV Nornen 16 m3	16 m3	Levert i Horten
	Harstad/Balder 22 m3			
		KV Nornen 22 m3	38 m3	Levert i Horten
	Oljevern 03 2 m3			Meldt at så langt er det tatt opp 47 m3 fra sjøen
	Ingeborg Platou 0,2 m3			
	KV Harstad + T/B Balder 18 m3			
	Oljevern 4 m3			Levert Skjærhalden ? Meldt at så langt er det tatt opp 67 m3 fra sjøen
20.02	KV Harstad ? m3	KV Nornen ? m3		Meldt at så langt er det tatt opp 90 m3 fra sjøen
21.02	KV Harstad 8 m3	KV Nornen 8 m3		Levert Langesund Meldt at så langt er det tatt opp 110 m3 fra sjøen
22.02	KBV Fartøy 44 m3 totalt			KV Nornen meldte inn at KVB fartøy totalt har levert 44 m3, men de mener selv å ha levert 53 m3....
	KV Harstad 13 m3			
25.02	Oljevern 01 24 m3 olje og oljeholdig is fra lensa som var rundt fartøyet tidligere.			
26.02	Oljevern 03 44 m3 olje og oljeholdig is fra lensa som var rundt fartøyet tidligere	KV Nornen 20 m3 oljeholdig is		Levert i Langesund
27.02	Oljevern 01 24 m3 olje og is			


Figure 4-26 Viscous oil due to low temperatures (Photo: NCA).

4.4.4 Recovery efficiency

Estimation of recovery efficiency

According to information from the Norwegian Coastal Administration, the estimated amount of bunker fuel oil released to sea during this incident was 112 m^3, calculated as water-free oil. Oil removed from the oil tanks on site was 123 m^3 and later at dock in Denmark 320 m^3 was removed

Oil type and properties

Only very limited physicochemical analyses were carried out for the bunker fuel onboard Godafoss. A density of 0,99 g/ml was measured for a sample from the "daytank" indicating a heavy fuel oil. A viscosity of 395 cP (shear rate $10s^{-1}$) measured at 50°C indicate that it was an HFO 380. The viscosity for the "fresh" (non-weathered) oil was at 1°C measured to 111 000 – 121 000 cP (shear rate $10s^{-1}$).

Modelling of oil weathering properties was not performed for this spill. Low temperature, "calm" weather conditions and the presence of ice gave low or very modest spreading of the oil slick. Based on experience from similar incidents and knowledge about the behaviour of heavy fuel oils, a very low degree of evaporation should be expected. In this case the evaporation was estimated to 1 % (approximately 1 m^3) of the spilt oil. Normally, entrainment of oil droplets in the water column would be in the same modest order of magnitude for such oil types. However, shear forces between ice floes promoted formation of oil droplets in the size of 1-2 mm, and such oil droplets were observed both under the ice and in the ice. A conservative estimate from the recovery operations indicates that as much as 10 m^3 of the oil spill was mixed into the water column as oil droplets.

Mass balance / oil budget

Because an oil budget was prepared shortly after the incident by the Norwegian Coastal Administration, the SINTEF Oil Weathering Model (OWM) has not been used to predict weathering properties for this incident. The oil budget prepared by NCA is presented in Figure 4-27. It includes amounts of oil that was removed from the vessel on site and later at dock in Denmark.

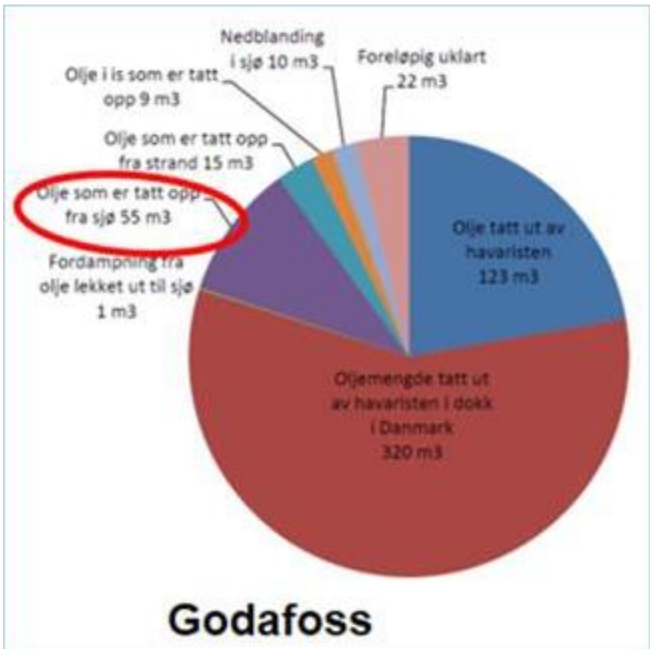


Figure 4-27 Predicted oil budget after the Godafoss oil spill (Source: Norwegian Coastal Administration).

Mass balance including recovery and estimation of efficiency

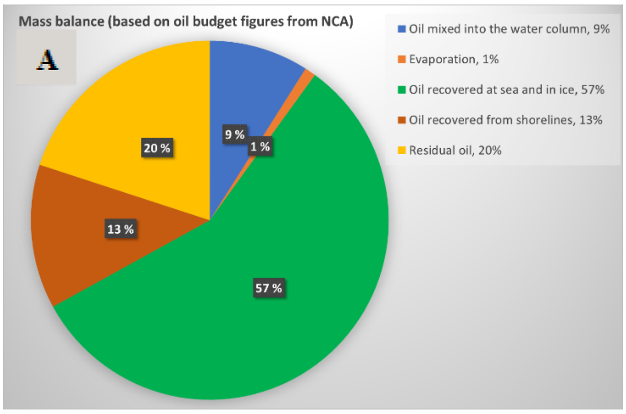
Table 4-8 sums up the NCA oil budget as presented in Figure 4-27, minus the amounts of oil removed from the vessel in a controlled manner. These figures are used to prepare the mass balance pie charts as presented in Figure 4-28.

Table 4-8 Input to mass balance calculations for Godafoss.

Parameter	Comments
Oil released 17/2 2011	112 m^3 of HFO 380 bunker fuel.
Recovered at sea	55 m^3 of HFO 380 bunker fuel calculated as "fresh" (non-weathered) oil.
Recovered in ice	9 m^3 of HFO 380 bunker fuel calculated as "fresh" (non-weathered) oil
Recovered on shorelines	15 m^3 of HFO 380 bunker fuel calculated as "fresh" (non-weathered) oil
Evaporated oil	1 m^3 of HFO 380 bunker fuel calculated as "fresh" (non-weathered) oil
Mixed into water column	10 m^3 of HFO 380 bunker fuel calculated as "fresh" (non-weathered) oil

In the further discussion about the efficiency of the mechanical recovery the amount of oil not available for mechanical recovery is deducted. In this case this means oil that has evaporated from the surface, oil that was mixed into the water column and oil that stranded.

Figure 4-28A shows the mass balance for the oil spilt to sea (112 m^3) based on the oil budget worked out by the Norwegian Coastal Administration (Figure 4-27). The oil recovered at sea and in ice adds up to 57 % of the total oil budget. 20 % of the released oil cannot be accounted for and is described as residual oil. By deducting the oil that is not available for mechanical recovery (Evaporated oil and oil mixed into the water column), the oil recovered at sea increases to 63 %, the oil recovered from shorelines to 15 % and the residual oil to 22 % Figure 4-28B).



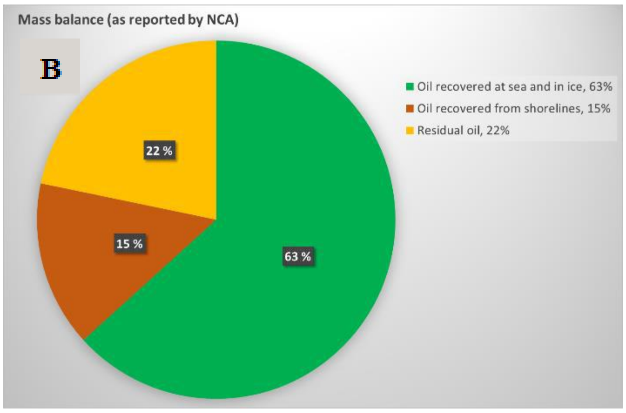


Figure 4-28 Mass balance including all parameters that was included in the oil budget (A) and with the amounts of oil that was not available for mechanical recovery deducted (B).

4.4.5 Conclusion

NCA reports that a maximum of 112 m^3 oil was spilled to sea from Godafoss and that the figure probably was lower due to an underestimation of the amount of oil taken out of the vessel at dock in Denmark. Anyway, the mechanical oil recovery at sea after the Godafoss spill was quite efficient. Low temperatures, calm weather conditions and the presence of ice gave low spreading of the oil. The evaporation was very low mainly due to the heavy bunker fuel (HFO 380) not containing any significant amounts of volatile components combined with the low spreading of the oil. Entrainment of oil droplets in the water column is also normally very low for such oil types, the calm weather conditions taken into consideration. However, oil mixed into the water column was estimated to 9% based on the action between ice floes making a shear that created large oil droplets that was pushed under the ice and incorporated in the ice.

The best estimation from the mechanical recovery at sea during the Godafoss spill is that 57 % of the oil spilt to the surface was recovered and this increases to 63 % if we look at the amounts of oil available at the surface for recovery.

4.5 Golden Trader (2011)

4.5.1 Sources of information

The following sources have been used as basis for the following incident:

- SHK, 2012. Swedish Accident Investigation Authority. Marine Safety Investigation report, joint safety investigation into the collision between the Maltese bulk carrier Golden Trader and the Belgian fishing vessel Vidar. Marine safety investigation Report No.: 18/2012.
- https://www.itopf.org/in-action/case-studies/case-study/golden-trader-denmark-2011/
- Kustbevakningen, 2011. Operation Kyrkesund. Pdf dokument.
- MSB & HaV, 2011. Oljepåslag på Tjørn 2011. En utvärdering av förberedelser, förmågor och hantering.

4.5.2 Description of the incident

On September 10th, 2011, bulk carrier Golden Trader (28 240 GT) collided with the fishing vessel Vidar (385 GT) 39 kilometres off the western coast of mainland Denmark releasing intermediate Fuel oil (IFO 180). The oil leak was caused by breach in the hull of heavy fuel oil storage tank no. 1 on starboard side (Figure 4-29). The first entry in deck log indicated no leakage to the environment. Following this, an estimated leak of 4 m^3 was reported. In the investigation report, SOK provides data indicating that the collision resulted in two oil spills where the spill drifting northward was more than 400 tonnes (released within a minute) while the southern part was 150 tonnes at the most.

Figure 4-29 Photos of Golden Trader after the collision with the fishing vessel Vidar (Source: Kustbevakningen, 2011).

Due to bad weather Golden Trader was allowed the following morning (September 11th) to anchor near Hanstholm, DK, followed by a move to Ålbæk Bight off Skagen, DK, on September 12th.

Five days after the collision (September 15th), the Swedish Accident Investigation Authority (SKH) reported to the Marine Satefy Investigation Unit (MSIU) regarding substantial large oil slick in Kyrkesund and around the island of Klädesholmen. To this point MSIU had only been aware of the collision.

On September 16th, 2011, oil was observed along the shoreline of the Swedish municipality Tjörn. The incident resulted in 15 km of coastline oiled to a significant degree while sporadic patches of stranded light oil observed as far as 150 km to the north, in Strömstad, and 15 km south of the main stranding area.

4.5.3 The response

The immediate response from the Danish Admiral Fleet (Søværnets Operative Kommando (SOK)) was to send its own environmental protection ships in the area to the incident site. At this point focus was on inspecting both vessels, collect oil samples from the heavy fuel oil storage tank, and inspect the validity of, inter alia, certificates, day logbooks, and the oil record book. SOK also detained both vessels. At this point, the Golden Trader crew informed SOK that it was believed that approx.1 m^3 of heavy fuel was spilled into the sea because of the collision.

In the evening of September 10th, SOK sent a SafeSeaNet (SSN) Situation Report to EU coastal States, Norway and Iceland. The report informed about the incident but made aware that the spill volume was unknown. In the email to the Norwegian Coastal Administration (NCA) that the spill volume, according to crew members, was approximately 1 m^3. In response to the report, no action was carried out by NCA or the Swedish Coast Guard/ Swedish Maritime Clearance (SMC). SOK did not send a pollution warning according to Bonn and Copenhagen agreement as the spill was not assessed as “likely to constitute a serious threat to the coast”.

Strategy

Based on the weather forecast, anticipating worse conditions SOK ordered Golden Trader to move towards shore, to seek shelter. Based on the forecast the vessel was first moved to Bay of Vigsø followed by a 2nd move to Bay of Ålbæk. No further pollution was reported during the transfer to Ålbæk.

On September 12th, a new SSN SITREP Report was issued and forwarded to the same recipiences as for the first report, informing that 60 m^3 of oil-water was collected. No response was received.

The strategy for operation was mechanical recovery. On morning the September 11th, a helicopter from SOK observed collectable oil with a calculated thickness of 1 cm. The size of the spill was estimated by SOK to about 150 tonnes. In the period from the 11th to the 12th, the environmental vessel GUTH collected an oil-water mixture of 60 tonnes where pure oil made-up 50 tonnes from the southward spill. At this point, the vessel experienced issues with its equipment due to bad weather.

On Tuesday 13th of September, A Danish surveillance aircraft observed oil traces on its Side Looking Airborne Radar (SLAR). Due to weather conditions, no recovery vessels were dispatched to the area. On 14th of September, SOK sent a request to the Swedish Coast Guard to carry out an aerial reconnaissance with SLAR in the area West of Hirtshals, no oil observed. 15th September first oil to Swedish coastline. First on the 16th, it became clear that the northward spill was from a major spill. Based on aerial observations the size was estimated to 25-30 tonnes, however, the oil layer was later discovered to have a thickness of up to 1 meter.

At sea the operation lasted days while the near shore and shoreline clean-up process was ongoing until November 5th. Several authorities involved in the decontamination operation with a larger number of employees and other resources. Two, non-profit organisation assisted. By October 2011, recovered 500 m^3 clean oil, after processing. High level of water prior to processing, indicative >50 % along the shore while 10 to 15 % 1-2 days after released into the water.

The Swedish Coastguard and the Swedish Civil Contingencies Agency (MSB) pollution response team used pumps, brush skimmers and mechanical excavators to recover the emulsified oil from the water. Booms were at an early phase 15th of September placed in Strømsund Bay to limit potential oil pollution (Figure 4-30). Swedish Army volunteers manually collected oil stranded along the coastline and conducted surveys of the many small islands impacted.

DNV SINTEF

Figure 4-30 Near shore boom location in Swedish waters on September 15th, 2011 (Source: Kustbevakningen, 2011).

The remaining oily debris and oil patches were removed by a local contractor over a total period of approximately fifteen months, with the municipality of Tjörn overseeing the work. An action plan regarding priorities and approved methods of cleaning in sensitive areas was developed by the Environment and Wildlife department of Tjörn. No chemical dispersion was applied during the operation.

External factors

The key external factor hampering the volume of oil recovered was the shifting weather conditions throughout the operation with wind up to 10 m/s combined with the fuel oil's characteristics making it feasible for a large oil slick/ spill (northbound) to remain unnoticed until reaching the Swedish shoreline.

Internal factors

Important internal factors that might have affected the recovery strategy were communication and oil type.

The change of oil characteristics, creating oil lumps when released from the vessel and submerged in the water column (subsurface) during rougher weather conditions combined with the information from the Golden Trader crew regarding spill size set the focus on the southern spill as this took place over a longer period and traces were observed. A factor that might have had an impact on the spill volume was the decision to move Golden Trader to sheltered water, based on the weather forecast.

In the mobilization and mechanical recovery phase, SOK immediately responded with one vessel which recovered an estimated $^{1}/_{3}$ of the southern bound oil spill within 2 days. Due to the weather conditions and equipment damage the operation was suspended at this point. The lack of feedback after SOK made neighboring countries aware of the incident is noted. With regards to shoreline cleanup in Tjörn county, on the Swedish west coast, a review carried out by Myndigheten for samhallsskydd och beredskap (MSB) og Havs och Vatten myndigheten (HaV) concluded that the municipality had limited knowledge about how to handle this kind of spill and what type of assistance they could expect from the national authorities. To improve the preparedness, the authorities recommend establish and communicate a real oil spill preparedness to increase knowledge and involvement of the correct units. In addition, participation in exercises is important.

4.5.4 Recovery efficiency

The total spill volume for the incident varies from 200 tonnes to more than 500 tonnes depending on source. The later one is based on the investigation report issued in connection with the incident. The larger volume includes two separate spill incidents: 400 tonnes released immediately after the collision followed by a 2nd spill of up to 150 tonnes over the next few hours caused by the vessel's motions.

The amount of recovered oil at sea corresponds while the collected oil near and along the shoreline varies from 500 m^3 of clean oil (investigation report) to 550 tonnes of emulsified oil (>70 % water content) (165 tonnes of pure oil) (ITOPF).

The presented numbers are used to illustrate the different outcome given dissimilar input data. The investigation report is used as baseline (Table 4-9).

Table 4-9 Fraction of recovered oil at sea.

<table>
<tr><th>Incident/activity</th><th>Comments</th></tr>
<tr><td>Oil release:
10/09, 2011</td><td>Oil spill in two parts: estimated approx. 400 m^3 (northbound) and approx. 150 m^3 (southbound) of IFO 180 oil. Investigation report indicates that the slick moving north was released within minutes. Oil density: 0.991 kg/l.
The oil is described as intermediate fuel oil (IFO 180).</td></tr>
<tr><td>Mechanical recovery</td><td>11/9-12/9: One vessel participated.
Totally 60 m^3 of product (oil-water mixture) was recovered. Estimated that 50 m^3 of this was oil residue. Water content in the emulsion 17 %. All from the southern moving slick.

13/9: Poor weather conditions – no recovery vessels sent to the area

14/9: No oil observed by aerial reconnaissance along the predicted trajectory based on observed oil the day prior.

15/9: First oil to shore reported. Slick moving north. Not observed in water column/water surface, all recovery took place along and on shore.

16/9: Identified as a major oil spill, demanding a full-scale operation from the Swedish Coast Guard.

14/10: Recovered 500 m^3 of clean oil, after processing. Estimated 50 % water content prior to processing.</td></tr>
<tr><td>Calculations</td><td><table>
<tr><th></th><th>Of total released oil volume a)</th><th>Of available oil volume</th><th>Comment</th></tr>
<tr><td>Recovered oil at sea (%)</td><td>9</td><td>33</td><td>Assumption that only the southbound oil was available for recovery</td></tr>
</table>
a) Includes the north- and southbound release.</td></tr>
</table>

4.6.6 Conclusions

- The knowledge and experience of the command team essential with regards to decision making (decision to move the vessel to sheltered water during the prevailing weather conditions)

- Weather conditions and oil type/characteristics important factors when it comes to the operational window and oil available for recovery.
- Open and transparent communication/dialogue with the crew on the damaged vessel essential to assess and evaluate the required level of preparedness.
- Overall, a total of 50 tonnes of fuel were recovered at sea from the southbound spill, indicatively 1/3 of the spill. Of the assessed total spill volume, of 500-550 tonnes)the recovered volume of pure oil was 9-10 %, where the norther bound spill is assessed to be sub-surface and therefore not available for mechanical recovery.

4.6 Full City (2009)

4.6.1 Sources of information

The information in this chapter is based on the following sources:

- PWC, 2010. Full City response evaluation report for the Norwegian Coastal Administration. PWC. 17.2.2010
- Lessons learned presentation from NCA (NCA, undated)
- Personal communication with NCA personnel involved in the response

4.6.2 Description of the incident

On the morning of July 30, 2009, the bulk carrier MV Full City sailed from Skagen in Denmark. The ship was then bunkered with about 1 100 tonnes of heavy oil and some diesel. The ship arrived at Langesund in Telemark, Norway, in themorning the same day. The ship was then in ballast and was to load artificial fertilizer on Herøya in Porsgrunn. While waiting to go to port, Full City anchored on Såsteinflaket outside Langesund, following instructions from the ship's agent. The ship then lay 0.9 nautical miles from the nearest land. Såsteinflaket is open to the Skagerrak and is unprotected from winds from the south. At the time of anchoring, a strong gale was blowing from the southeast, and the wave height was estimated to be 2-4 meters. A storm warning was sent over the radio.

During the evening the weather got worse, and the wind increased to a strong gale, at the same time as it turned from southeast to southwest. The wave height was calculated to be 4-6 meters. Full City swayed fast and stomped hard into the sea. Information from the AIS system showed that the ship began operating ashore just before midnight, and shortly after midnight Breivik VTS contacted the vessel with information that the vessel was drifting, and information was requested about the situation. The captain tried to get the vessel going and control the situation, but this failed. Full City grounded at 00:23 at Såstein. At 00:37, the captain requested assistance. Vessels were then sent to evacuate the crew. Due to bad weather and sea, it was not possible to get tows on board.

4.6.3 The response

Strategy

Large resources participated in the response and the inter-municipal committee against acute pollution (IUA) in Telemark, Vestfold and Aust-Agder was mobilized. In addition, the Civil Defence and the Home Guard assisted. IUA Østfold, Vest-Agder and Kristiansand were also put on standby. Oil spill response equipment from the NCA depot in Horten and Kristiansand was mobilized. In addition, the Norwegian Coastal Administration's surveillance aircraft and a helicopter assisted in obtaining an overview from the air. The Norwegian Coastal Administration's depot forces from Svalbard in the north to Kristiansand in the south were used. The Coast Guard assisted with vessel resources. The Swedish Coast Guard did the same.

Figure 4-31 Full City 2nd of August 2009 (Photo: NCA).

Resources used in the sea-going operation included:

- The Norwegian Coastal Administration's vessels (6 vessels)
- The Coast Guard (3 vessels - incl. 1.daughter-craft)
- The Swedish Coast Guard (3 vessels), as well as surveillance aircraft
- Sjøheimevernet (4),
- Skjærgårdstjenesten, local vessels, tugs etc.

In total, 7 different mechanical recovery systems were operated at sea:

- The Norwegian Coastal Administration (2)
- The Coast Guard (3)
- NOFO (1)
- Current Buster (1)
- Harbor Buster (1)

External factors

Strong winds and high seas meant that the damage to the ship increased during the night before the ship settled on the grounds outside Såstein. The vessel suffered extensive hull damage which resulted in oil spills. This polluted the coastline, including several protected areas and bird sanctuaries. The Norwegian Coastal Administration received notification of the grounding at 00:50. The rescue operation was led by the Main Rescue Center. Shortly after large parts of the crew from Full City were evacuated, the Norwegian Coastal Administration launched a state-led oil spill response operation.

The spill caused pollution in the area from Stavern in Vestfold to Lillesand in Aust-Agder, and about 200 positions were polluted with oil. Among other things, 37 protected nature and bird areas and geologically protected areas were contaminated by oil. In addition, many outdoor areas and private properties were soiled by oil. More than 2 000 seabirds died as a direct cause of the incident.

Internal factors

The commander of the coastguard ship KV Nornen was appointed site manager for the seagoing operations (SKL-Sjø). Sea-going vessels were subject to SKL-Sjø. The Norwegian Coastal Administration sent an adviser to SKL-Sjø (KV Nornen). When the person in question lived in Tromsø, it took a little longer to get an adviser on board than if there had been an adviser available closer to the place of action. The Norwegian Coastal Administration has prepared a functional plan with a checklist for SKL-Sjø. The functional plans have not been made sufficiently available to the Coast Guard since it is only available in the Norwegian Coastal Administration's internal contingency plan. The functional plan for advisor SKL-Sjø is described in the cooperation agreement between the Coast Guard and the Norwegian Coastal Administration and is part of KYBAL14, and shall be available in the vessel's KYBAL folder. Advisor SKL-Sjø was established to assist SKL-Sjø / Ship Manager with oil spill response expertise, secure information flow, access to logs, networks and coordination between the action management and SKL-Sjø, as well as insight into the Norwegian Coastal Administration's planning. This was important, among other things, because the Coast Guard does not have access to the Norwegian Coastal Administration's operational planning. SKL-Sjø experienced a great responsibility both as captain of its own vessel and as leader of the oil spill response operation at sea.

Figure 4-32 The acute phase at the shorelines (Photo: NCA)

SKL-Sjø experienced that the information they received about oil observations was characterized by it not being sufficiently analyzed and verified. Among other things, SKL-Sjø received large amounts of images, which took a long time to download. Sweden's way of utilizing the surveillance aircraft proved to be very effective. An operator on board the aircraft had the task of observing where the oil was and directing vessels towards where the oil was. SKL-Sjø experienced that IUA did not have sufficient competence for the use of oil spill response equipment and capacities on board seagoing vessels. Allocated resources were therefore not used well enough to collect oil in bays and coves.

According to SKL-Sjø, initial notification was quick and efficient. Since the incident took place in the middle of the joint holiday, there was somewhat lower availability for resource persons and actors. On the other hand, the incident took place in central parts of Eastern Norway, where there is good availability of resources. SKL-Sjø had good experiences with conducting short status meetings for new participants in the campaign. The meetings were conducted by VHF and telephone. SKL-Sjø had to deal with the individual IUA leaders. Coordination was made difficult since the IUA handled the action differently and the IUA had limited knowledge of seagoing capabilities. It was therefore challenging to establish a common understanding of the situation and difficult for SKL-Sjø to make priorities for the effort, including coordinating IUA's sea-going units in the beach zone with other sea-going action. The call-up of Sjøheimevernet's (SHV) forces was made without this being coordinated with SKL-Sjø. The SHV forces were added to IUA on request but were eventually subordinated to SKL-Sjø as part of the sea-going operation. In terms of command, SHV was led by SHV staff in Stavern. SHV planned with an advanced link in Langesund, which was not desirable from SKL-Sjø. There was an unclear division of roles within the Norwegian Coastal Administration about who should handle the dialogue with the casualty. The shipwreck section in the emergency department handled contact with the shipping company and salvage company in the beginning. During this period, SKL-Sjø did not have sufficient information about what was happening on board the casualty. The dialogue with SMIT Salvage was not perceived by SKL-Sjø as optimal. The Norwegian Coastal Administration sent POLREP to the Coast Guard's central management, but POLREP was not forwarded to Swedish vessels. A contributing reason for this was, according to the Coast Guard, that the ship Langeland sank the same night, and there was a confusion between "Langesund" and "Langeland". Kystverk Rederi has specific tasks in oil spill preparedness, and oil spill response equipment is also stationed at Oljevern 01-04. The Norwegian Coastal Administration has stated that broader training experience could make vessels and crews better prepared for an oil spill response operation with regard to equipment, procedures and coordination, etc.

KV Nornen received technical assistance from the Norwegian Coastal Administration. The logistics support was at times somewhat confusing. An advanced depot was established, but it was challenging to have a good overview of available material, including where the material was located and when the material had arrived at the depot for collection. In one case, there was a period in which the material had arrived for collection, without being notified to KV Nornen.

HSE had a high focus throughout the period. The Coast Guard traditionally has a high focus on HSE and this worked well during the operation. SHV was to a lesser extent prepared for the HSE challenges in an oil spill response operation. They did not wear protective clothing and were poorly informed. These were briefed on board the Coast Guard. HSE was a topic at all meetings and was high on the agenda.

4.6.4 Recovery efficiency

Estimation of recovery efficiency

According to information from the Norwegian Coastal Administration (NCA), the estimated amount of bunker fuel oil released to sea during this incident was 294 tonnes, calculated as water-free oil. The first phase after the groundingwas a rescue operation and the oil spill response operation commenced when the first phase was terminated. NCA's priority for the on-sea response operations was to prevent the oil from reaching vulnerable areas and natural resources, recovery of free-floating oil, prevention of re-mobilization of oil from shorelines and surveillance by use of helicopter and aircraft. The grounding took place nearshore with short drifting time to shorelines.

Oil type and properties

It was reported that the vessel had approximately 1005 tonnes of heavy fuel oil (IFO 180) and 120 tonnes of diesel onboard. There are very few physicochemical data reported for the oil, but one sample taken at sea during the acute phase had a viscosity of 52000 cP (18 °C; shear 10s-1) and a water content of 42 %.

Mass balance / oil budget

An oil budget was prepared by the Norwegian Coastal Administration. Of the total of 1 154 tonnes of oil that was on board the Full City, 27 tonnes were taken up in sea operation, 74 tonnes were taken up in beach operation, 860 tonnes were pumped from the vessel and 191 tonnes of oil remained in the environment. Figure 4-33 illustrates the oil budget from the Full City incident. Predictions of the weathering properties of the oil seems not to have been performed, and processes like evaporation and oil mixed into the water column was not part of the original oil budget. The weather was rough at the time of the grounding and the weathering of the oil could have been significant in the initial phase.

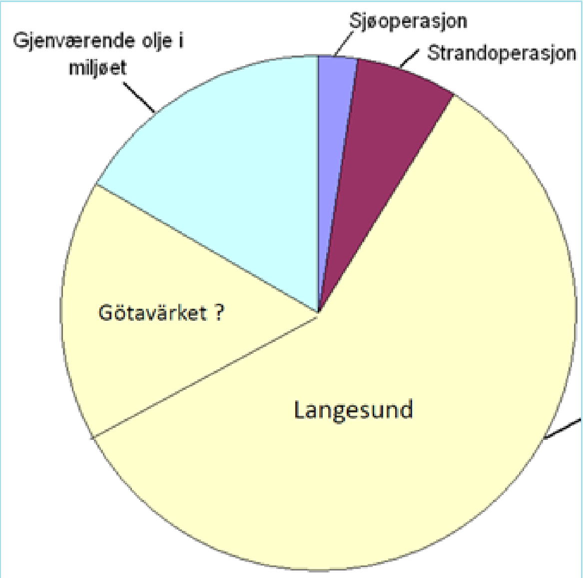


Figure 4-33 Estimated oil budget after the Full City oil spill (Source: Norwegian Coastal Administration).

Mass balance including recovery and estimation of efficiency

To try to estimate an efficiency of the mechanical recovery operation at sea as a function of the amount of oil available for recovery on the sea surface, the SINTEF OWM was used to predict weathering properties for a release of an IFO 180 bunker fuel (Figure 4-34). A sea water temperature of 15 °C and a wind speed of 10 m/s have been used as input tothe predictions. If we assume that the oil, as an average, was weathered for two days before recovery, the evaporation would have been approximately 3 % and the oil mixed into the water column or being submerged would have been approximately 15 %.

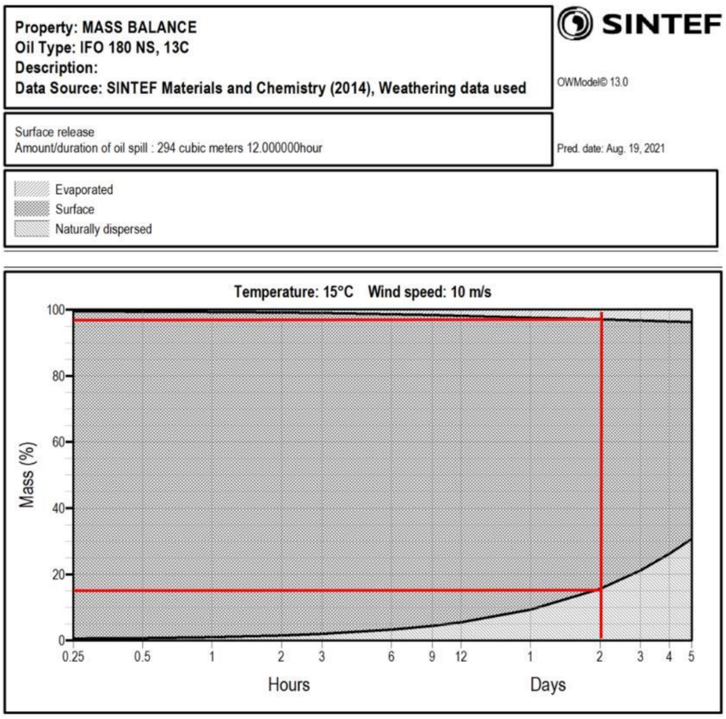


Figure 4-34 Predicted mass balance of an IFO 180 bunker fuel like the oil released from Full City. Sea temperature of 15 °C and wind speed of 10 m/s.

Table 4-10 sums up the NCA oil budget as presented in Figure 4-33, minus the amounts of oil removed from the vessel in a controlled manner. These figures are used to prepare the mass balance pie charts as presented in Figure 4-35.

Table 4-10 Input to mass balance calculations for Full City.

Parameter	Comments
Oil released 31/7 2009	294 tons of IFO 180 bunker fuel.
Oil recovery at sea	28 tons of IFO 180 bunker fuel calculated as "fresh" (non-weathered) oil.
Oil recovery on shorelines	74 tons of IFO 180 bunker fuel calculated as "fresh" (non-weathered) oil
Evaporated oil	3% which equals 9 tons of the IFO 180 bunker fuel calculated as "fresh" (non-weathered) oil
Mixed into water column	15% which equals 44 tons of the IFO 180 bunker fuel calculated as "fresh" (non-weathered) oil

Figure 4-35A shows the mass balance for the oil spilt to sea (294 tonnes) based on the oil budget worked out by the NCA (Figure 4-33) combined with predictions of oil evaporated and mixed into the water column and which is regarded not available for mechanical recovery. The oil recovered at sea accounts for only 10 % of the total release. Asmuch as 47 % of the released oil cannot be accounted for and is described as residual oil. By deducting the oil that is regarded as not being available for mechanical recovery, the oil recovered increases to 11 % and the residual oil to 58 % (Figure 4-35B). 2-3 times more oil was recovered from shorelines compared to the sea surface.

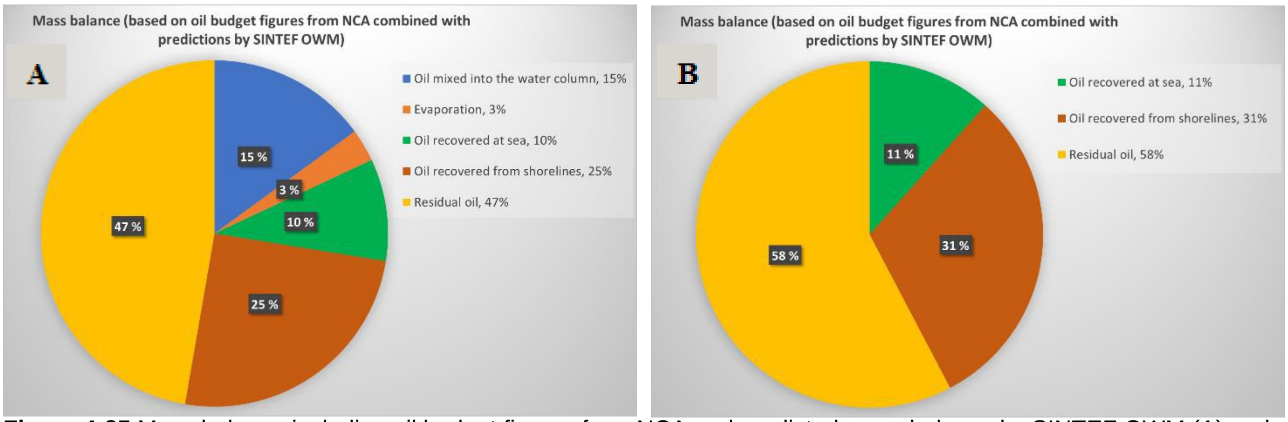


Figure 4-35 Mass balance including oil budget figures from NCA and predicted mass balance by SINTEF OWM (A) and with the amounts of oil that was not available for mechanical recovery (evaporated oil and oil mixed into the water column) deducted (B).

4.6.5 Conclusion

The oil amounts recovered from the sea surface was modest for the Full City spill. This is due to several factors where proximity to shore probably is the most important. The oil hit shorelines short time after the release started and shorelines were polluted over long distance from the release point and down the south-east coast of Norway. Due to the near-shore drift of the oil it was challenging to perform on-sea recovery operations. A large part of the oil spilt from the vessel (191 tonnes) was described as oil remained in the environment. Oil that is evaporated, mixed into the water column or submerged in the water is probably part of this. However, a main part of this fraction probably consisted of stranded oil that could not be recovered, in Figure 4-35 called residual oil.

Only 11 % of the released oil available at the surface was recovered mechanically at sea. However, there are reasonable explanations why this figure was low. A similar spill in more open waters would probably have given higher recovery numbers, the oil type taken into consideration.

4.7 Rocknes (2004)

4.7.1 Sources of information

The information in this chapter is based on the following sources:

- NCA, 2004. Rocknes incident report from the Norwegian Coastal Administration (“Rocknes”-ulykken. Rapport fra Kystverket. 23.november 2004”).
- SINTEF, 2004. SINTEF report on oil analyses and oil budget from the spill (“Rocknes – analyser av oljene ombord og oljebudsjett. Foreløpig rapport”.) Date: 2004-08-30.
- Personal communication with NCA and previous NOFO personnel involved in the response.

4.7.2 Description of the incident

The cargo ship M / S Rocknes grounded on 19 January 2004 at approximately 16:30 at Revskolten lighthouse near Bergen. The ship quickly began to dock and went all the way around in less than a minute. The ship was loaded with about 23 000 tonnes of rock and had 470 m^3 of heavy oil and 70 m^3 of diesel on board. Of a crew of 28, 18 died, including the ship's captain.

The Vessel Traffic Service (VTS) notified the Norwegian Coastal Administration's emergency department at approximately 16:45. IUA Bergen (intermunicipal responder) was notified and was part of the Norwegian Coastal Administration's action organization with regard to beach and land response, while the Norwegian Coastal Administration concentrated on theresponse at sea.

Figure 4-36 Rocknes position in Vatlestraumen (Photo: NCA)

4.7.3 The response

The shipping company itself considered the measures to secure the ship, while the Norwegian Coastal Administration supervised the handling of the vessel. 18 people were missing after the accident and it was assumed that many of them were inside the vessel. The police were responsible for securing the casualty and the nearest area around for the sake of the rescue work. It was not relevant to start an oil spill response operation near the casualty before the rescue work was completed. At the same time, it was established that it was impossible to search for the missing as the vessel lay upside down, not stable and held in place by other ships. It was therefore planned to move the ship to port where searches for the missing could be carried out. Shipowners started work with insurance companies and salvage specialists to try to reduce the risk of pollution.

Strategy

Oil collection at sea was initiated when the area was released after the rescue operation on 19 January at 23:43. The first oil booms were in operation on January 20 at 00:20.

The Norwegian Coastal Administration's accident manager at sea ("SKL/S") was initially on board the Norwegian Coastal Administration's oil spill response vessel "Oil spill response 01". January 20 at 04:00 the coastguard vessel KV "Ålesund" arrived and SKL/S 'task was then transferred to the captain of this vessel. During the night 19.-20. January, several units were deployed in the oil spill response operation. At 05:00, three recovery systems were in action. In the extraordinary situation, a significant number of boats and other resources were mobilized or acted on their own initiative. Later on 20 - 21 January, there was a large influx of companies and individuals who offered their services and resources with a view to combating oil pollution. Some also put private equipment into the oil spill response operation without clearance from the action management. Measures to prevent further spread of oil from the vessel and collection of free oil from the sea were implemented with up to seven towed oil recovery systems. Nevertheless, it was inevitable that oil that could not be captured inland would hit land. Therefore, several booms were inserted that led oil into bays and straits that had already been hit by oil. Here it could be more easily controlled and recorded. During the naval operation, several types of oil-fighting equipment were used.

External factors

Vatlestraumen is a narrow sound affected by tidal currents, and the response at sea had to adjust to the changing tides as the current for periods was too strong for effective recovery (Figure 4-37).

Figure 4-37 Oil moving with tidal currents in Vatlestraumen (Photo: NCA).

Internal factors

The individual participating units in the recovery operation at sea achieved very different results with regard to the amount of oil recovered. Some took up a lot of water relative to oil, and various level of training of the responders were pointed out as one of the reasons for this. A need for analysis of the efficiency of the recovery equipment was also adressed after the incident. All the recovered water was delivered for treatment, which increased the cost of the response. A too high threshold for requesting transport was also adressed in the post spill report, as well as limited surveillence information about estimated spill-volumes. Normally, the aircraft at the Coastal Administration's disposal are able to give good estimates of the amount of oil that is at sea. During this operation, the action management received little information from the aircraftregarding the assessment of the amount of oil. The reason for this was that the oil was largely along land and in bays and coves. It was, on the other hand, confirmed that helicopters are a very appropriate surveillance tool inland, especially for detailed investigations, and overviews of the oil's distribution was good.

When the vessel was ready to be moved, there was little free-flowing oil left at sea. The shipowner was ordered to establish a comprehensive contingency plan for the moving to prevent new oil that may have been released during towing from causing increased pollution. On 28 January, the ship was moved to Coast Center Base near Ågotnes. By agreement with the shipping company, the Norwegian Coastal Administration took care of the emergency preparedness. Despite extensive emergency preparedness measures, some oil was released, and further collection was needed at sea. Upon arrival, the ship was rigged with oil booms and after the casualty was turned around and no longer represented any danger of pollution, the oil spill response measures at the vessel were terminated.

On January 29, there was no longer actionable free-flowing oil left at sea. Thus, the demobilization of the participants in the maritime oil spill response campaign was initiated. Participating ships were sent for cleaning before they were allowed to leave the action area. Due to the secondary risk of pollution, a large number of vessels now had to be cleaned. The cleaning plant did not have the capacity to handle this and entailed some waiting both for the equipment to be delivered for cleaning at CCB and for cleaning the ships at the Onyx plant.

4.7.4 Efficiency

Rocknes was a serious accident and salvage of life had priority at an early stage. The first booms for oil recovery were launched shortly after midnight the 20. January. According to information from the NCA, the estimated amount of fuel oil onboard Rocknes was 470 m^3 heavy fuel oil and 70 m^3 diesel. It has not been presented any figures on how much of this was released to sea. In the further calculations we assume that all the heavy fuel oil was released to sea while the diesel is not included. The grounding took place nearshore in an area with strong currents and with short drifting time to shorelines for an oil spill.

Oil type and properties

The heavy bunker oil onboard Rockness was a HFO 380.This was a mixture of oils bunkered at Esso Skålevik (Density: 0.974 kg/l; Viscosity: 37000 cP (5 °C and shear 10 s-1)) and Shell Rotterdam (Density: 0.991 kg/l; Viscosity: 47500 cP (5 °C and shear 10 s-1)). Physicochemical analyses of the Rockness indicated that it was more similar to the Skålevik bunkered oil, and this oil was used as a basis for prediction of the weathering properties at sea for the Rocknes oil by use of the SINTEF OWM. Analyses of samples of weathered Rocknes oil gave water uptakes up to 50 % and viscosities up to 237000 cP.

Mass balance / oil budget

The SINTEF OWM has been used to predict weathering properties for the Rocknes HFO 380, including mass balance without any recovery data included. The sea temperature in the area was measured to 5 °C. Predictions are performed at both 5 and 10 m/s wind speed. It is assumed that all the HFO 380 onboard (458 tons) was leaking to sea over a period of 24 hours. In the further evaluation it is assumed that the oil, on average, drifted for 2 days before it was recovered. Figure 4-38 shows the predicted mass balance at 5 and 10 m/s wind with an indication of the mass of oil (in percent) that was evaporated (upper red line) and mixed into the water column (lower red line) after 2 days drifting time on sea.

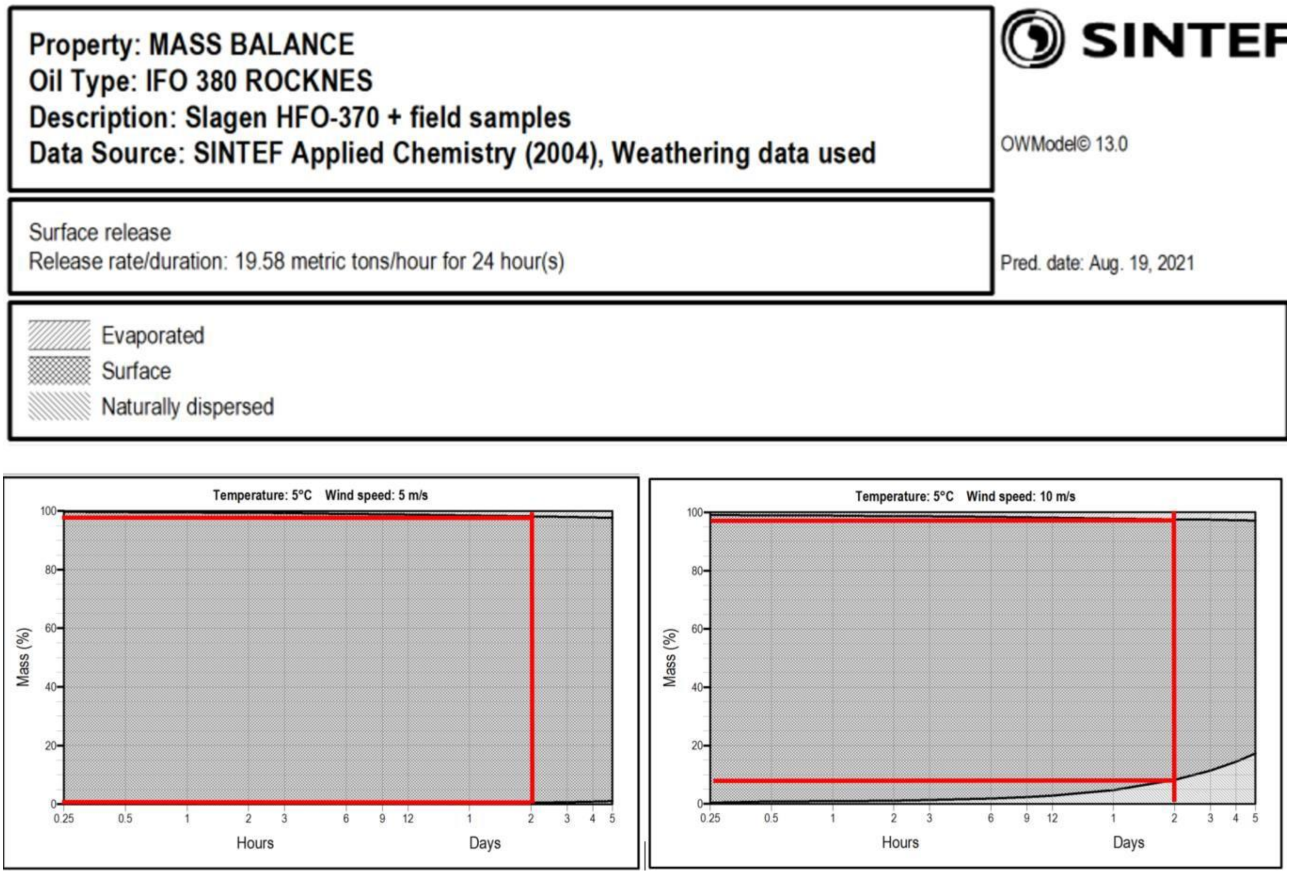


Figure 4-38 Predicted mass balance of the HFO 380 bunker fuel from Rocknes. Sea temperature of 5 °C and windspeed of 5 and 10 m/s.

Mass balance including recovery and estimation of efficiency

Table 4-11 summarize the assumptions and input parameters used to prepare the mass balance for Rocknes.

Table 4-11 Input to mass balance calculations for Rocknes (Continues on next page).

Parameter	Comments
Oil released 19/1 2004	The vessel had 470 m^3 heavy fuel oil (HFO 380) onboard. With a measured density of 0,974 kg/l this gives 458 tonnes. There is no information on how much was spilt, soin the further calculations it is assumed that the entire amount of HFO 380 was released to sea. 70 m^3 of diesel onboard is not included in the calculations.
Oil recovery at sea	141 tonnes of HFO 380 calculated as "fresh" (non-weathered) oil.
Oil recovery on shorelines	85 tonnes of HFO 380 calculated as "fresh" (non-weathered) oil

Evaporated oil	At 5 m/s wind speed: approximately 2 % which equals 9 tonnes of the HFO 380calculated as "fresh" (non-weathered) oil At 10 m/s wind speed: approximately 3 % which equals 14 tonnes of the HFO 380 calculated as "fresh" (non-weathered) oil
Mixed into water column	At 5 m/s wind speed: approximately 1 % which equals 5 tonnes of the HFO 380 calculated as "fresh" (non-weathered) oil At 10 m/s wind speed: approximately 8 % which equals 37 tonnes of the HFO 380 calculated as "fresh" (non-weathered) oil

Figure 4-39 shows the mass balance for the oil spilt to sea (458 tonnes) at 5 and 10 m/s wind speed. The evaporation is almost the same for the two wind speeds, but the mass of oil mixed into the water column increases considerably from 5 to 10 m/s. Residual oil, which is the difference between oil spilt and oil evaporated, mixed into water column and recovered, constitutes a large fraction of the total mass balance, but because there is uncertainty about the amount of oil spilt the figures for residual oil are correspondingly uncertain. The amount of oil recovered mechanically at sea is estimated to 31 % of the total release.

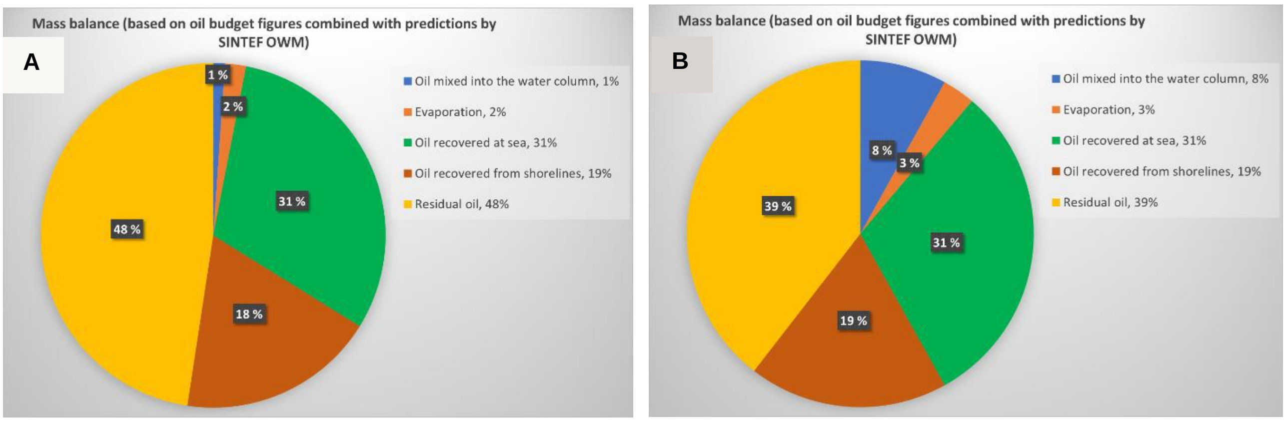


Figure 4-39 Mass balance based on total amount of spilled oil (458 tonnes) at 5 m/s (A) and 10 m/s (B) wind.

If we look at the oil that theoretically was available for mechanical recovery (evaporated oil and oil mixed into the water column deducted) on the surface, the amount of oil increases to 32 or 35 % depending on the wind strength (Figure 4-40). The increase is due to a decrease in residual oil at increasing wind speed because more oil is removed from the surface by mixing into the water column.

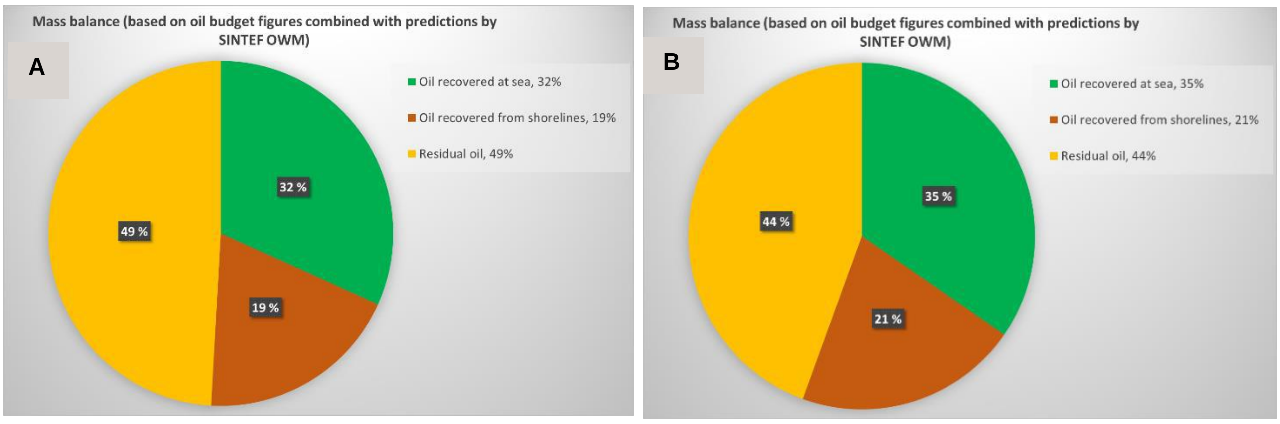


Figure 4-40 Mass balance based on surface oil available for mechanical recovery (evaporated oil and oil mixed into water column deducted) at 5 m/s (A) and 10 m/s (B) wind.

4.7.5 Conclusion

Despite challenging conditions with narrow waters and short drifting time to shorelines the efficiency of mechanical recovery at sea was high for the Rocknes incident. The portion defined as residual oil is relatively high, but the figures are very uncertain due to uncertainty about how much oil was released to sea. Almost 10 days after the vessel went on ground it was towed to the Coast Centre Base (CCB) at Ågotnes. More oil was released, and some was lost during this operation, indicating that not all the original oil was released at the grounding site.

Because oil recovered at sea and on shorelines was strongly infested by debris, bark, and other things it was very challenging to prepare an oil budget based calculated as pure oil. Combined with uncertainties about the amount of oil spilt the figures are very uncertain as already underlined in report from the incident.

4.8 Fu Shan Hai (2003)

4.8.1 Sources of information

The information in this chapter is based on the following sources:

- Andersen; R.N., JD-Contractor A/S, 2013 Emptying the Fu Shan Hai of oil. Presentation pdf format.
- Danish Maritime Authority, 2003. Collision between Chinese bulk carrier FU Shan Hai and Cypriot container vessel Gdynia. Casualty report. Date: August 7, 2003.
- Christiansen, B., M., 2003. 3D. Oil drift and Fate Forecast at DMI. Technical Report No. 03-36. Danish Meteorological Institute, Denmark.
- Pålsson, Jonas & Hildebrand, Lawrence & Linden, Olof. (2017). Limitations of the Swedish coordination capacity for large oil spills. International Oil Spill Conference Proceedings. 2017. 2017040. 10.7901/2169-3358-2017.1.000040.
- SCG, 2003. Swedish Coast Guard Operation Fu Shan Hai - Kustbevakningen.html

4.8.2 Description of the incident

On May 31st, 2003, a collision between the Chinese bulk carrier Fu Shan Hai and the Cypriot container ship Gdynia occurred in the Baltic Sea, 5,6 km NNW of Hammer Odde, Bornholm, Denmark (Figure 4-41). The Chinese vessel took in water immediately and capsized. The Coast Guard vessel KBV 202 offered the Danish authorities to tow the wreck to shallower water to reduce the risk of uncontrolled oil spills. The Danish authorities declined but asked that KBV 202 stay nearby. A couple of hours later, the Coast Guard received a request from Denmark for towing. KBV 202 managed to tow Fu Shan Hai 1.5 nautical miles but was forced to cancel as it was obvious that the ship would sink shortly. Shortly afterwards, Fu Shan Hai sank to a depth of 65 meters (Figure 4-42).

Fu Shan Hai carried 1 680 tonnes of fuel oil IFO 380, 110 tonnes of diesel and 35 tonnes of lube oil, a total of 1 825 tonnes. The vessel was carrying a cargo of 66 000 tonnes, fertilizer from Ventspils, Latvia.

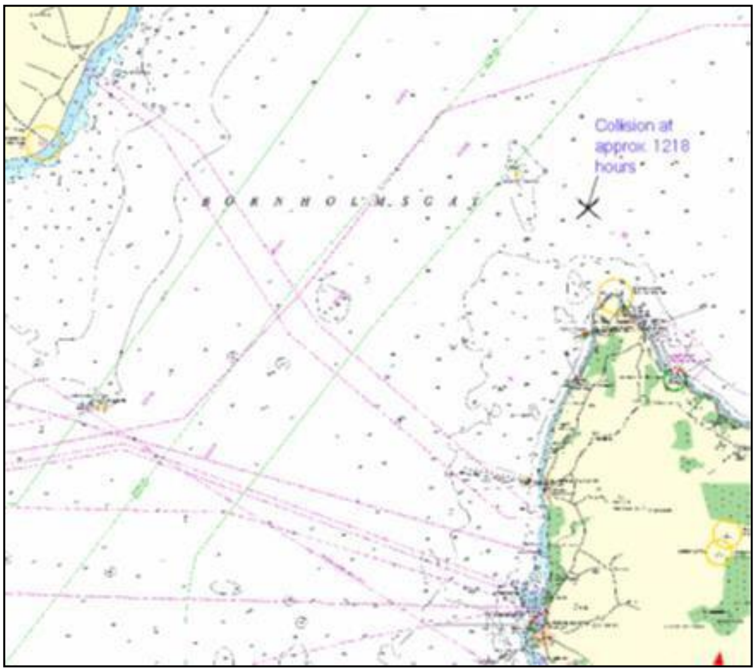


Figure 4-41 Collision location between Fu Shan Hai and Gdynia (Source: Danish Maritime Authority, 2003).

Figure 4-42 Fu Shan Hai at time of sinking after the collision with container ship Gdynia (Source: SCG, 2003).

4.8.3 The response

The approach was mechanical recovery involving Swedish, Danish and German resources. Three days after the spill (on June 3rd) 500 tonnes of oil was recovered. At the same time, it was feared that 100 tonnes of remaining oil were approaching the Swedish coast in the Skåne region. At this point the ship was still leaking oil and oil reached the shore south of Simrishamn. Within the first week of operation a total of 1 000 tonnes of oil and water mixture was recovered atsea. At the end of the first week, changes in weather conditions caused oil to be transported off the Scanian shoreline. The prevailing weather conditions combined with less oil availability reduced the mechanical recovery efficiency at sea.

Over the following two weeks, Danish vessel was continuously present at the spill site while three Swedish environmental vessels were standby while the air force monitored the area continuously. During this period the vessel was still leaking oil, though less than in the earlier phase; however, the weather conditions were assessed as severe, and no vessels were actively recovering oil. In this phase, the wind blew in an offshore direction (westward), transporting the oil away from the west coast of Sweden.

Strategy

As described above the strategy was to tow the damaged vessel to a shallower area, to reduce the risk for uncontrolled oil spill. At sea, mechanical recovery was initiated early on and the resource pool included Danish, Swedish and German resources during the first week. During the 2nd week the weather conditions worsened, from 4-8 m/s the first week to 15-16 m/s in periods during the 2nd week keeping three Swedish environmental vessels on standby.

On the monitoring side, a Danish vessel was next to the wreck site at all time and aerial surveillance was applied.

The Swedish Coast Guard positioned an 800 m boom to limit the impact along the shoreline. A total of 78 m^3 of oil was recovered along the Swedish shoreline while 10 m^3 along the Danish shore.

Remaining oil in wreck was recovered in two diving operations, 2003 and 2013, respectively. A total of 1 134 tonnes oil were recovered in these operations.

External factors

The weather during the incident was clear with wind speed of 6 m/s. Relative calm weather within the 1-week after the incident made it feasible for the recovery vessels to operate during this time slot. At the same time, the conditions transported oil to shore. In the following week, severe weather resulted in no recovery (vessels standby), while at the same time the wind was blowing westward and transporting oil away from the Swedish shore. Harsher weather conditions also contributed to submerge the oil in the water column.

The change of oil characteristics over time results in a high-viscous emulsion containing up to 65 % water after 3 days at sea, from approximately 38 % after 1 day, which meant large volumes to be handled by the recovery vessel. A density like seawater (0.992 kg/l vs. 1.005 kg/l) makes the oil suitable for submersion with increased wave motions while re-entering on water surface in calmer weather.

Internal factors

In the early phase after the incident, the Danish authorities monitored the situation and within a couple of hours decided to tow Fu Shan Hai to a shallower area (with the assistance of the Swedish Coast Guard) to limit the risk for an uncontrolled spill. The operational command requested early on assistance from Sweden and Germany as well as initiated recovery at sea. In addition, continuous spill site and oil drift surveillance were a part of the strategy.

The quick response ensured a relative a high degree of recovered oil at sea within the 1st week – 1 000 tonnes of oil andwater mixture.

The Swedish Coast Guard (Kbv 202 used Lamor brush system) while the Danish vessels (Gunnar Seidenfaden) used Ro Desmi skimmer. Due to diverse number of systems and time of operation, no effectiveness number for one given system is available.

An aspect that was put forward following the incident was the requirement for strengthening the preparedness network between neighbouring municipalities, by establishing an Incident Management System for national cross-organizational emergencies, such as large oil spills. Even more, the requirement for more cross-organizational exercises is needed to build capacity and the necessary inter-organizational relationships.

4.8.4 Recovery efficiency

The calculation of mechanical recovery efficiency assumes that diesel and lube oil have the same characteristics as fuel oil, the main hydrocarbon product onboard Fu Shan Hai.

There are uncertainties about how much oil was released to sea during this incident, but we estimate that approximately 706 m^3 oil was spilt and that the spill mainly consisted of IFO 380. The weather conditions were favourable for mechanical recovery the first week after the spill and most of the oil recovered at sea seems to have been taken up in that period. Besides, the distance to shore (5-6 km) was positive for recovery operations at sea.

Oil type and properties

SINTEF received 6 samples of weathered oil sampled at sea and on shorelines. The samples taken at sea had a density of 0,992 – 0,995 kg/l, a water content varying from 38 % to 65 % and a viscosity of 30 500 – 46 000 cP (measured at 12 °C and a shear rate of 10 s-1). It was concluded that the oil was an IFO 380, and a similar oil was foundin the SINTEF OWM database and used for prediction of weathering properties of the oil spilt.

Mass balance / oil budget

The SINTEF OWM has been used to predict weathering properties for the Fu Shan Hai IFO 380, including mass balance without any recovery data included. The sea temperature in the area was measured to 12 °C and a temperatureof 10 °C was used as input to the model. Predictions are performed at both 5 and 10 m/s wind speed, but because mostof the oil seems to have been recovered under low-wind conditions the first week, only the 5 m/s wind prediction has been used in the further evaluation. In the further evaluation it is assumed that the oil, on average, drifted for 2 days before it was recovered. Figure 4-43 shows the predicted mass balance at 5 and 10 m/s wind with an indication of the mass of oil (in percent) that was evaporated (upper red line) and mixed into the water column (lower red line) after 2 days drifting time on sea.

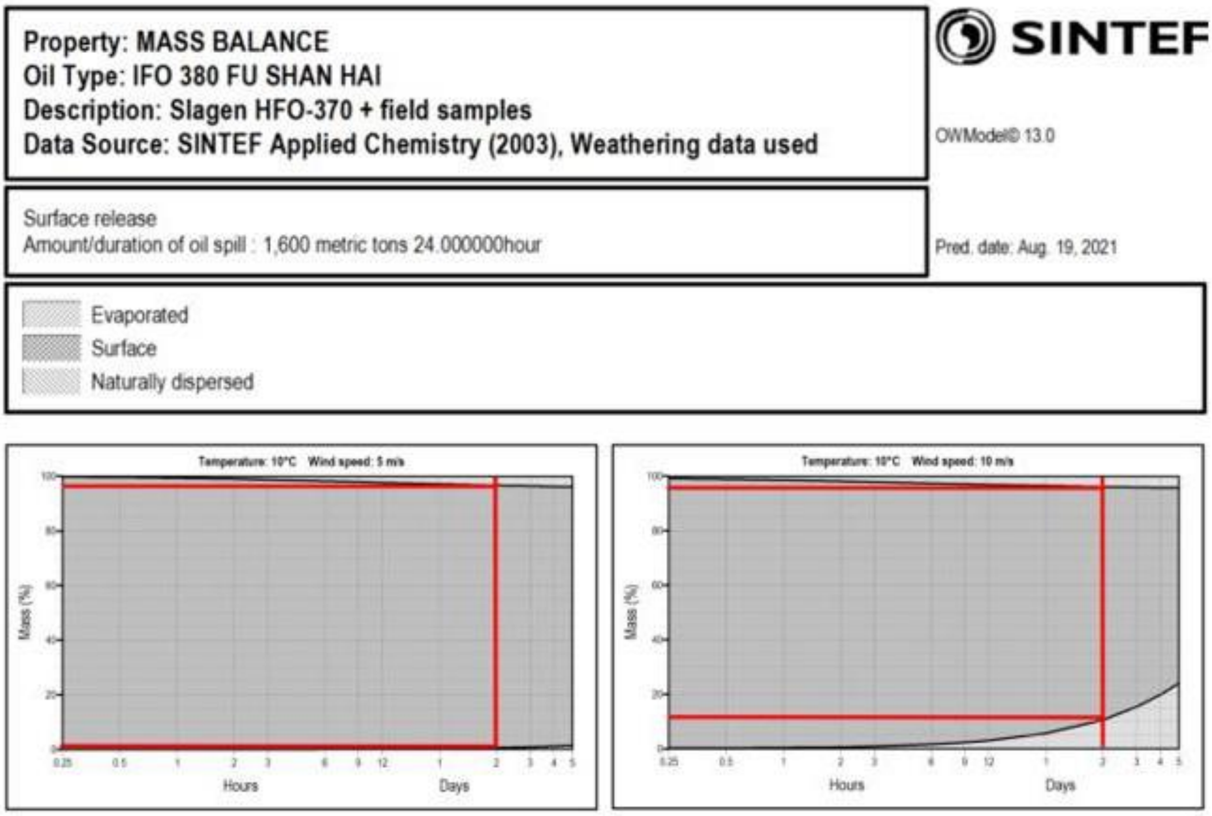


Figure 4-43 Predicted mass balance of the IFO 380 bunker fuel from Fu Shan Hai. Sea temperature of 10 °C and windspeed of 5 and 10 m/s.

Mass balance including recovery and estimation of efficiency

Table 4-12 sums up the assumptions and input parameters used in the mass balance calculations for Fu Shan Hai.

Table 4-12 Input to mass balance calculations for Fu Shan Hai (Continues on next page).

Parameter	Comments
Oil released 31/5 2003	The vessel had 1 680 tonnes heavy fuel oil (IFO 380), 110 tonnes diesel and 35 tonnes lube oil onboard, giving a total oil amount of 1 825 tonnes. Using the density for the IFO 380 (0,991 kg/l) for all the oil onboard, the total volume would be 1 842 m^3. It was reported that 1 136 m^3 oil was removed from the wreck by diving operations.

	By deducting that from the total volume onboard, it can be estimated that 706 m^3, calculated as pure oil, was spilt to sea. For simplicity, it is assumed that this amount consists of IFO 380.
Oil recovery at sea	Up to six Swedish, four Danish and two German vessels participated the first week (1/6 – 8/6). The following week poor weather conditions for carrying out mechanical recovery. Swedish vessels recovered 220 tonnes of liquid (1/6 and 2/6). 750 tonnes of liquid were recovered 3/6. It is estimated that in total 528 m^3 of IFO 380, calculated as "fresh" (non-weathered) oil, was recovered mechanically from the water surface.
Oil recovery on shorelines	89 m^3 of IFO 380 calculated as "fresh" (non-weathered) oil
Evaporated oil	At 5 m/s wind speed: approximately 2% which equals 9 m^3 of the IFO 380 calculated as "fresh" (non-weathered) oil At 10 m/s wind speed: approximately 3% which equals 14 m^3 of the iFO 380 calculated as "fresh" (non-weathered) oil
Mixed into water column	At 5 m/s wind speed: approximately 1% which equals 5 m^3 of the iFO 380 calculated as "fresh" (non-weathered) oil At 10 m/s wind speed: approximately 8% which equals 37 m^3 of the iFO 380 calculated as "fresh" (non-weathered) oil

Figure 4-44 shows the mass balance for the oil spilt to sea (706 m^3) at 5 m/s wind speed. It shows that the contribution from evaporation and mixture of oil into the water column is low for this oil type at the chosen wind speed. The mass of oil recovered at sea is very high and the mass of oil that is mot accounted for (residual oil) is low. If we deduct oil that is naturally removed from the surface (evaporated and mixed into water column), as in Figure 4-44B, the mass of oil recovered at sea is estimated be 80%.

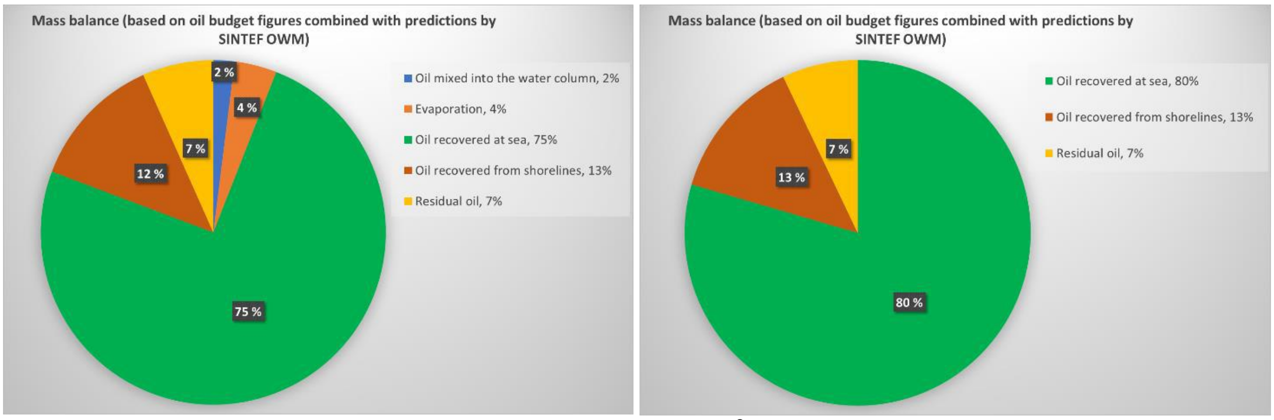


Figure 4-44 Mass balance based on total amount of spilled oil (706 m^3) (A) and surface oil available for mechanical recovery (evaporated oil and oil mixed into water column deducted) (B) at 5 m/s wind.

4.8.4.1 Conclusion

We have not found any figures in the available documents indicating how much oil was released to sea during this incident. The figure used in these calculations (706 m^3) was estimated by deducting the oil removed from the wreck by diving operations from the entire amount of oil onboard. Therefore, mass balance estimations have a high degree of uncertainty. However, the mechanical recovery operation at sea appears to have been quite efficient. There were optimal weather conditions the first week after the collision when most of the oil seemed to have been recovered and the distance from shore was favourable for mechanical recovery.

Other findings

- The knowledge and experience of the command team essential with regards to decision making (e.g., decision to tow the vessel to shallower water to ensure better spill control and bring in preparedness resources
- Weather conditions and oil type/characteristics important factors when it comes to the operational window
- Efficiency of different recovery equipment unclear due to factors such as operational time for each system and if all vessels from Sweden were equipped with Lamor brush system and the Danish vessels with Ro Desmi skimmer. Based on the total recovered volume of 528 m^3 of pure oil within the first week, an estimated 80 % of available oil on sea surface was recovered.
- Quick mobilization time of resources, effective 1st week of recovery, 2nd week weather conditions not suitable for recovery at sea.
- Better networking and training required for shoreline operation to enhance the level of preparedness for potential future incidents.

4.9 Prestige (2002)

4.9.1 Sources of information

- IOSC, 2005. Evaluation of the response by specialised foreign vessels to the release of oil from Prestige. Conference contribution by Tim Wadsworth, a senior coordinator at The International Tanker Owners Pollution Federation (ITOPF) with involvement in many international spills.
- Albaigés, J., Morales-Nin & Vilas, F., 2006. The Prestige oil spill: A scientific response. Marine Pollution Bulletin 53, pages 205-207.
- Gonzales, M., Utiarte, A., Pozo, R. & Collings, M., 2006. The Prestige crisis: Operational oceanography applied to oil recovery, by the Basque fishing fleet. Marine Pollution Bulletin 53, pages 369-374.
- IOPC funds, 2020. Prestige. Pdf document.
- Per Gustav Steimler, 2021. First-hand experience from recovery operation participant. Pers.- comm. June, 2021.

4.9.2 Description of the incident

On November 13th, 2002, the Bahamas registered tanker Prestige (81 564 DWT), carrying 76 972 tonnes of IFO 650 fuel oil, began listing in bad weather and leaking oil 56 km off Cabo Fisterra (Galicia, Spain) (Figure 4-45). On November 19th, while under tow, the vessel broke in two and sank 260 km west of Vigo (Spain) at a depth of more than 3 560 meters. An estimated 13 700 tonnes of the cargo remained in the wreck, indicating a release of approximately 63 200 tonnes of heavy oil fuel. Between May and September 2004, some 13 000 tonnes of cargo were removed from the fore part of the wreck. Approximately 700 tonnes were left in the aft section.

The weather persistent oil type combined with the existing current and wind conditions resulted in stranded oil along the west coast of Galicia and the Bay of Biscay (Spain and France), northern part of Portugal with traces along the shoreline of UK (the Channel Islands, Isle of Wight and Kent).

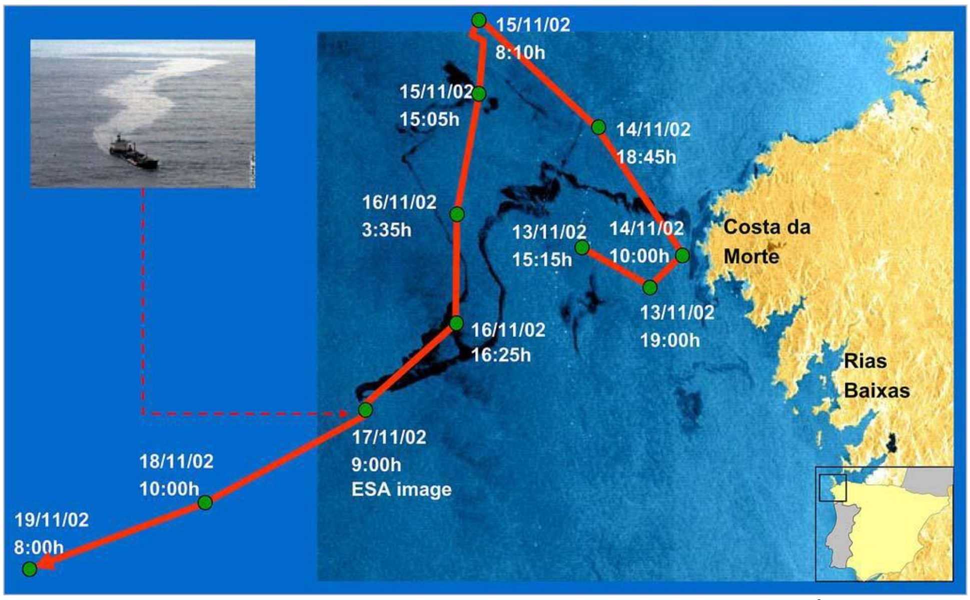


Figure 4-45 Prestige spill location and towing route offshore (Source: Albaigés et al., 2006).

4.9.3 The response

Based on the size of the spill and the prevailing current conditions the Spanish authorities requested assistance from neighbouring states via bilateral agreements and from states further away through Civil Protection Co-operation Mechanism of the European Commission (EC). Oil drifting into Portuguese waters similar request made by Portuguese navy. Entering French waters, French vessels remained under the control of French authorities.

Over the following month, major fleet assembled with sixteen vessels from eight nations (Table 4-13).

Table 4-13 Overview of foreign recovery vessels participating in the clean-up operation after Prestige oil spill (IOSC, 2005)

Country of home port	Vessel	Port of departure
Belgium	UNION BEAVER	Antwerpen
Denmark	GUNNAR SEIDENFADEN	Korsør
France	AILETTE	Brest
	ALCYON	Brest
Germany	NEUWERK	Cuxhaven
Italy	AQUA CHIARA	Porto Tórres
	TITO	Livorno
Netherlands	ARCA	Scheveningen
	RIJNDELTA	Rotterdam
Norway	FAR SCOUT/BOA SIW*	Mongstad/Trondheim
	NORMAN DRAUPNE/BAMSE*	Trondheim/Stavanger
	NORTHERN CORONA	Aberdeen, U.K.
United Kingdom	BRITISH SHIELD	Annaba, Algeria
	SEFTON SUPPORTER	Liverpool

* FAR SCOUT and NORMAN DRAUPNE were accompanied by BOA SIW and BAMSE to facilitate deployment of boom.

Strategy

The strategy for operation was mechanical recovery at sea (carried out by offshore vessels), near shore (fishing vessels) and shoreline clean-up. No chemical dispersion was applied during the operation.

The first foreign offshore vessel (AILETTE) arrived on November 14th, the day after the beginning of the spill. The 2nd vessel (RUNDELTA) arrived in Spain on the 19th of November. The last vessel (NORMAND DRAUPNE) arrived on December 29th.

The offshore operational phase lasted from November 14th, 2002, to February 11th, 2003. The volume of recovered oil peaked during the first month of operation.). The vessels used a diversity of skimmers, with the overall conclusion that the efficiency declined over time with change in oil characteristics.

In the early phase, the recovered rate was good due to the oil’s fluidity and high concentration.

For the near shore operation, fishing vessels were applied. Their increased manoeuvrability, compared to the offshore vessels, made them suitable for recovering oil in these waters and collect plate of oil too small and to spread out for the larger specialized vessels. Low freeboard allowed manual collection of oil by long-handled scoops, and mechanically by use of nets and trawls and grabs attached to vessel cranes.

Lack of response to immediate needs in the early weeks of the crisis, highlighted the weakness of the decisional frameworks and organisational capacity. In the absence of a contingency plan, first cleaning operations ashore were based on the massive response of thousands of volunteers. The shoreline clean-up resulted in approximately 15 % (3 196 tonnes) of the volume gathered at sea. For 1 tonne of oil recovered 4-5 tonnes of beach material (oil together with sand and seaweed) were handled.

External factors

The key external factor hampering the volume of oil recovered was the shifting weather conditions throughout the operation with wind up to 13-17 m/s med swells up to 5 meters. The tidal currents had an impact in the onshore operation.

The conditions limited the operational window of the systems to various degree, depending on boat size and equipment as well as caused large homogenous slicks of oil (100s of metres in diameter and tens of centimetres thick) to fragment the slicks into smaller patches (<5 m in diameter). By January, the oil had weathered to small plates and tar balls.

Internal factors

The change of oil characteristics over time, slicks breaking into smaller patches and potentially being submersed in the water column, resulted in more time searching for oil than recover. Early on site, near spill location, would therefore be beneficial with regards to oil mechanical oil recovery.

Mobilization time was a critical parameter. Early responders recovered more oil compared to the later ones due to more available oil.

The oil type and weather conditions hampered the operational process, however, vessel characteristics combined with type of skimmer system had impact on a single system's effectiveness. Vessels with high freeboard allowed deployment of containment and recovery equipment in rougher conditions. Larger storage tank would also be beneficial for the offshore vessels, limiting the number of trips to shore (Table 4-14).

Table 4-14 Storage capacity of foreign recovery vessels (m^3)

Vessel	Storage capacity (m3)	Vessel	Storage capacity (m3)
TITO	290	NEUWERK	1,000
UNION BEAVER	~300	NORTHERN CORONA	1,000
G. SEIDENFADEN	310	ARCA	1,060
AILETTE	500	ACQUIA CHIARA	1,084
ALCYON	500	SEFTON SUPPORTER	1,350
NORMAND DRAUPNE	798	RIJNDELTA	3,548
FAR SCOUT	1,000	BRITISH SHIELD	3,835

In terms of skimmers the main categories were disc skimmers, weir skimmers, sweeping arms and brush skimmer (Table 4-15). The disc skimmer was the least effective skimmer causing the crew on ACQUIA CHIARA to continue collecting oil by using grab and trawl net. The reason for this being the oil characteristics and the water-in-oil emulsion resulting in the disc's availability to remove oil from the surface. The Transrec skimmer worked well in the early phase due to oil concentration and fluidity. With increased viscosity and fragmentation, the efficiency declined. The sweeping arms allowed for a more flexible adjustment according to the weather conditions. Placing the arms alongside the vessels' hull reduced pumping distance to storage tank. Due to fiction in the system the system was not operating optimal. The Brush skimmer was applied by one vessel in sheltered waters detecting limited volume of oil. Based on limited operational time the system was not evaluated.

Table 4-15 Skimmer types available on foreign recovery vessels.

Type	Vessel	Skimmer description
Disc	ACQUIA CHIARA/ TITO	OCS disc skimmer & 400m of Mannesmann Offshore Boom.
Weir	AILETTE/ ALCYON	Transrec 250 weir skimmer with Hi-Wax adapter, Foilex 250 weir skimmer & 300m high-sea boom
	FAR SCOUT/ NORMAND DRAUPNE	Transrec 250 weir skimmer with Hi-Wax adapter & 400m of Ro-Boom 3500 boom
	GUNNAR SEIDENFADEN	DESMI Terminator weir skimmer & 1,000m of Ro-Boom 2000 boom
Sweeping Arm	ARCA	2 x 13.5m sweeping arms
	NEUWERK/ RIJNDELTA/ SEFTON SUPPORTER	2 x 15m sweeping arms
Brush	UNION BEAVER	2 x Lori brush skimmers

The command central in charge of such a large operation with multinational participants requires a highly experienced leadership and communication skills to ensure an optimal outcome during the existing conditions. In this case, the command in Spain was carried out by SASEMAR and in France D'ENTRE-CADSTEAUX. In addition to the control units, it is important to have in mind the individual foreign vessel's (crew's) experience in international operation like Prestige.

As part of the strategy, the Spanish leadership team, decided to tow the vessel offshore on November 14th. This movement of the ship given the prevailing weather conditions has been responsible for increased leakage (as much as 40 000 tonnes) and a serious of "oil waves" arriving at the Spanish, Portuguese and or French coasts.

In the near shore areas, the implementation of a high number of fishing vessels (180) recovered more oil compared to the offshore specialised recovery vessels. This was due to high flexibility and the possibility of chasing smaller patches of oil.

4.9.4 Recovery efficiency

It is estimated that approximately 64 000 m^3 of IFO 650 was released to sea from Prestige over a period of several months. There were shifting weather conditions with wind up to 17 m/s. The oil type is normally regarded as challenging when it comes to oil recovery operations. At the same time, it formed thick layers of homogenous slicks that could be beneficial for mechanical recovery. Stranding of oil was reported along coastlines in several countries, but we have not found any specific figures for oil recovered on shorelines, so this has not been included in further estimations.

Oil type and properties

SINTEF received 5 samples of weathered oil sampled at sea and 1 sample of oil from the vessel tanks. The weathered samples were taken during a period of approximately 3 months weathering at sea. The sample of the oil taken onboard Prestige had a density of 0,995 kg/l and a viscosity of 43 400 cP (at 15 °C and shear rate 10 s-1). The weathered samples had a density of 1,009 – 1,013, a water content of 45 – 60 % and a viscosity of 83 500 – 297 000 (at 15 °C andshear rate 10 s-1). It was concluded that this was an IFO 650 oil. A similar oil was found in the SINTEF OWM databaseand used for prediction of weathering properties of the oil spilt.

Mass balance / oil budget

The SINTEF OWM has been used to predict weathering properties for the Prestige IFO 650, including mass balance without any recovery data included. The sea temperature in the area was measured to 12 – 15 °C and a temperature of 15 °C was used as input to the model. Predictions are performed at both 10 and 15 m/s wind speed, because the oil was spilt far offshore in the winter season with normally high wind conditions. In the further evaluation it is assumed that the oil, on average, drifted for 5 days before it was recovered. Figure 4-46 shows the predicted mass balance at 10 and 15 m/s wind with an indication of the mass of oil (in percent) that was evaporated (upper red line) and mixed into the water column (lower red line) after 5 days drifting time on sea. Because this oil forms emulsions with high density, close to sea water density, it will be over-washed by seawater as the wind speed increases. The term "Naturally dispersed" in the prediction, therefore, represent over-washed oil and not oil droplets. It may re-surface when the wave activity decreases.

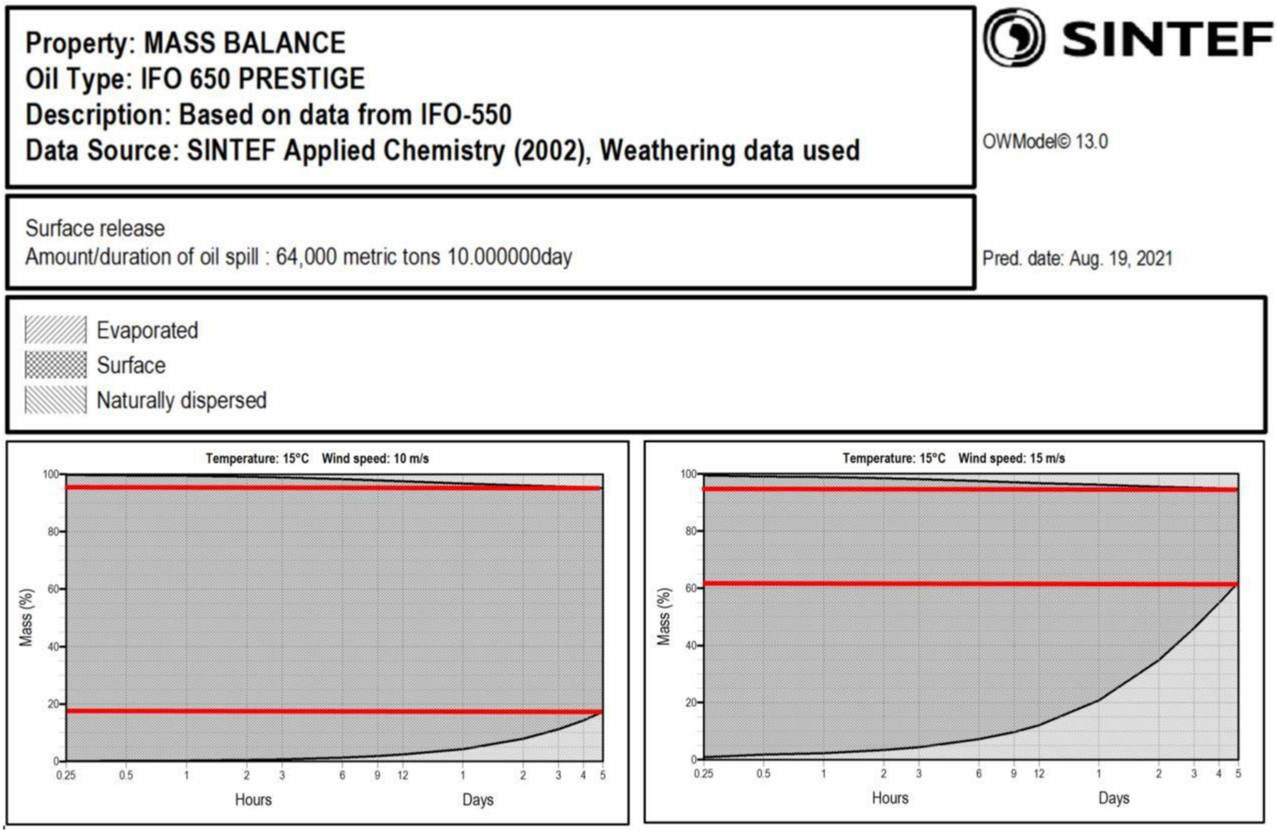


Figure 4-46 Predicted mass balance of the IFO 650 bunker fuel from Prestige. Sea temperature of 15°C and wind speed of 10 and 15 m/s.

Mass balance including recovery and estimation of efficiency

Table 4-16 sums up the assumptions and input parameters used to prepare the mass balance for Prestige.

Table 4-16 Input to mass balance calculations for Prestige (Continues on next page).

Parameter	Comments
Oil released starting 13/11 2002	The vessel was carrying 76 972 tonnes of IFO 650 fuel oil. The density was measured to 0,995 kg/l, giving 77 359 m^3 IFO 650. 13 700 tonnes were reported as remaining oil in the wreck after it sank. The amount of oil released to sea during this incident was then estimated to 63 700 tonnes (64 000 m^3). The oil release started 13/11 but the vessel broke in two and sank at 3 500 m 19/11. After it sank, the vessel continued to leak but at a declining rate. Oil recovery operations were ongoing from the start of the release until 11/2-2003.

Oil recovery at sea	It is reported that totally 17 000 tonnes of a mixture of oil and water-in-oil (w/o) emulsion was recovered by specialized offshore vessels and 35 500 tonnes of a mixture of oil and water-in-oil (w/o) emulsion was recovered by fishing vessels. Water content in the emulsions varied between 45 to 60 %. In the further calculations it is assumed that the oil recovered by fishing vessels was at sea (not shorelines), that the mean water uptake was 50 % and that the oil/water mixture recovered (totally 52 500 tonnes) consists of a w/o emulsion with 50% water. This gives: 26 250 tonnes of pure oil. The density of the oil at that point is estimated to be around 1 kg/l which give a volume of 26 250 m^3 IFO 650 recovered.
Oil recovery on shorelines	It is reported that approximately 12-15 % of the HFO recovered at sea wasrecovered on land. This gives approximately 3 196 tonnes.
Evaporated oil (from predicted mass balance)	At 10 m/s wind speed: approximately 5 % which equals 1 312 m^3 of the IFO 650 calculated as "fresh" (non-weathered) oil At 15 m/s wind speed: approximately 6 % which equals 1 575 m^3 of the IFO 650 calculated as "fresh" (non-weathered) oil
Mixed into water column – submerged (from predicted mass balance)	At 15 m/s wind speed: approximately 17 % which equals 4 463 m^3 of the IFO 650 calculated as "fresh" (non-weathered) oil At 15 m/s wind speed: approximately 62 % which equals 16 275 m^3 of the IFO 650 calculated as "fresh" (non-weathered) oil

Figure 4-47 shows the mass balance for the oil spilt to sea (64 000 m^3) at 10 and 15 m/s wind speed. The contribution from evaporation is low and is not much influenced by increasing wind speed. The mass of oil mixed into the water column increases significantly with increasing wind speed. This is heavy oil that is over-washed by sea water when the wave activity increases with increasing wind speed. This submerged oil may come back to the surface in calm weather conditions and as such be available for mechanical recovery. A substantial portion of this oil release was reported as being recovered mechanically (41 % of the total oil release). The portion of oil denoted as residual oil is likely a mixture of oil remaining on the surface (e.g., tar balls), oil on shorelines and sunken heavy oil/emulsion.

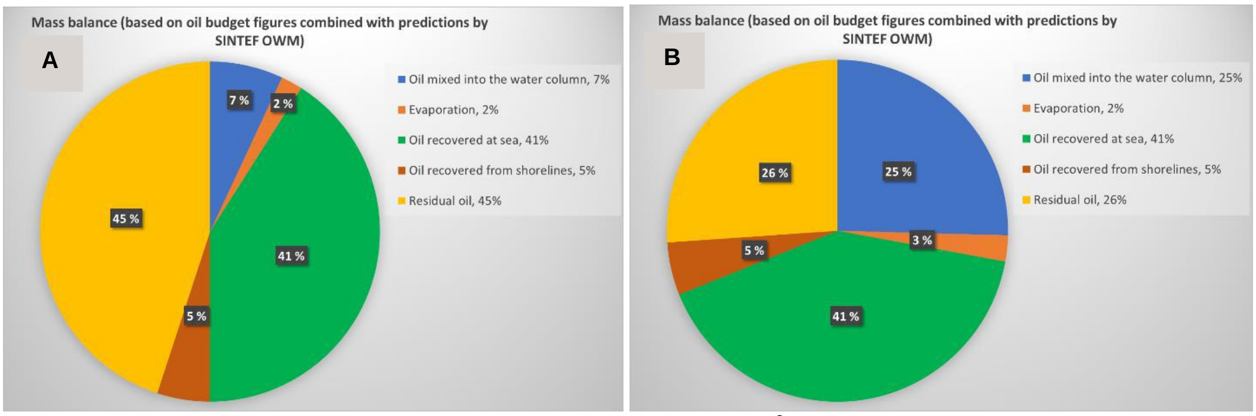


Figure 4-47 Mass balance based on total amount of spilled oil (64 000 m^3) at 10 m/s (A) and 15 m/s (B) wind.

If we assume that the fraction of oil that is evaporated and mixed into the water column as submerged oil is not available for mechanical recovery, the mass balance can be estimated as Figure 4-48.

Depending on the wind conditions it is estimated that between 45 % to 57 % of the oil available on the surface was recovered.

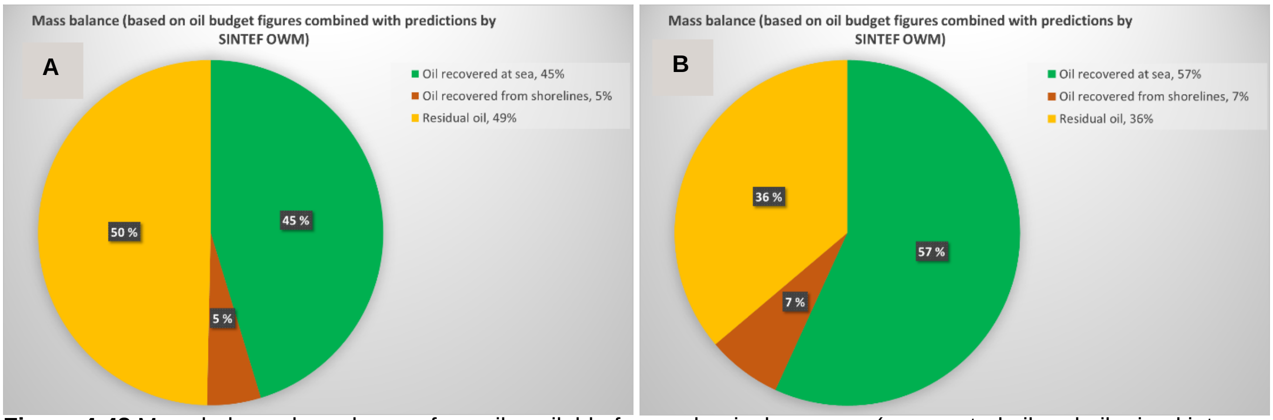


Figure 4-48 Mass balance based on surface oil available for mechanical recovery (evaporated oil and oil mixed into water column deducted) at 10 m/s (A) and 15 m/s (B) wind.

4.9.5 Experiences from the field

In addition to the information provided above, the project team interviewed Per Gustav Steimler on June 15th, 2021, a NOFO employee participating in the recovery operation, first onboard the NOFO-vessel Far Scout (Figure 4-49) and later the NOFO-vessel Norman Draupne, with the intention to receive first-hand inputs.

Command:

- Initially poorly organized in Spain. The order was “If you see oil, pump oil” – after that left to themselves.
- Tactics using 1 nautical mile between operational systems, could have been reduced to ½ nm, would have increased efficiency.
- During the first period, very little support from remote sensing, oil slick spotted visually. Limited work to daytime.
- Later (France) support from a “spotter” plane which detected oil from the air and used flare smoke to signal oil location.

Equipment:

- When the skimmer was full of oil it became too heavy to lift over the deck rail.
- They had a skimmer in reserve, but this was not identical to the first one – this made taking spare parts from one to the other complicated. Having a mechanic on board proved essential.

Figure 4-49 Operation from NOFO-vessel Far Scout (Source: Per Gustav Steimler).

Mobilizing:

- More efficient if they arrived earlier on the scene when the oil was more concentrated.
- Delayed due to lack of space at the quay.
- Oil spill mitigated by bringing the ship to shore (“Offerbukt”) and not towing it offshore.

Unloading:
The thickness of the oil required heat to get the oil out of the tanks.

HSE:

- Crew safety was priority. Important to keep deck clean (avoid slippery deck).
- Important with establishing dirty and clean zones onboard the vessels
- Important with a good brief and debrief for the personnel each day

4.9.6 Conclusion

Also for Prestige there are uncertainties regarding both amounts of oil released and oil recovered. We have used the figures reported in available documentation and combining that with predictions of weathering properties and mass balance by use of SINTEF OWM and we estimate a relatively high efficiency. For simplicity, we have assumed that the mixture of oil and water-in-oil (w/o) emulsion reported to have been recovered, consisted of a 50 % w/o emulsion. This could also have included some free water, debris etc., which in our calculations would have decreased the fraction of recovered oil.

The Prestige oil was a heavy oil floating deeply in the sea and easily being over-washed by waves. When running the SINTEF OWM at constant wind (10 and 15 m/s in this case), the over-washed and submerged oil is regarded as being unavailable for later recovery. This is a limitation with this approach and is further discussed in paragraph 2.5. The fraction of the oil that is regarded as being over-washed may re-surface in calmer weather and as such being available for recovery. This adds to the uncertainty for the Prestige calculation. The figures presented here as oil recovered at sea are probably quite optimistic and the fraction of recovered oil is probably lower. Besides, some of the oil reported to be recovered by fishing vessels may be oil recovered on shorelines.

Other findings

- The knowledge and experience of the command team essential with regards to decision making (e.g. decision to tow the vessel further offshore during the prevailing weather conditions)
- Weather conditions and oil type/ characteristics are key factors when it comes to the operational window
- In bad weather, larger ships are preferable (more safeboard, can work longer at sea without risking the crew's safety).
- Skimmer type, dependent on oil type and weathering characteristics
- Quick response to international call important (most of the oil was recovered at an early stage). Important with good leadership.
- Use of fishing vessel in near-shore waters, important for recovering minor slicks.
- In total 1/3 of the released oil were mechanically recovered at sea, respectively 1/3 by the offshore vessels and 2/3 by the fishing boats. Taking into consideration factors such as evaporation and down-mixing using SINTEF's OWM model the recovery efficiency as fraction of available oil is estimated to 45-57 % (depending on wind conditions).

5 DISCUSSION

The cases described in the previous chapter represents a wide spectrum of incident types, spill types and response operations. In this chapter the key questions for the study are discussed based on the findings:

- How much of the spill was recovered at sea?
- How much of oil available for mechanical recovery was recovered?
- Which factors (internal and external) affected/limited the recovery?

5.2 Recovery efficiency ratios

An overview of the studied spills, estimated recovery ratios, and reported limiting factors for mechanical recovery are listed in Table 5-1.

Table 5-1 Overview of the spills, estimated recovery ratios and reported limiting factors for mechanical recovery (Footnotes on next page).

	Year	Name	Type of incident/spill	Recovery of spilled oil (%)[a)]	Recovery of available oil (%)[b)]	Reported limiting factors for mechanical recovery
Petroleum incidents	2010	Macondo[c)]	Blowout offshore (Deep subsea)	4 %	10 %	• Response strategy • Aerial misguiding • Debris/seaweed • Operational restrictions
	2009	Montara[d)]	Blowout offshore (topside)	9 %	13-22 %	• Response strategy • Oil properties
	2003	Draugen	Spill from pipe offshore (subsea)	23 %	44-51 %	• Delayed response • Surveillance/remote sensing • Slick patchiness
Ship incidents	2011	Godafoss	Ship grounding	57 %	63 %	• Low temperatures and sea ice
	2011	Golden Trader[e)]	Ship collision	9 %	33 %	• Oil properties • Weather conditions • Strategy/decision making
	2009	Full City	Ship grounding	10 %	11 %	• Weather conditions • Nearshore
	2004	Rocknes	Ship grounding	31 %	32-35 %	• Nearshore • Tidal currents • Tactics
	2003	Fu Shan Hai	Ship collision	75 %	80 %	• Oil properties • Strategy/decision making • Weather conditions
	2002	Prestige	Ship (tanker) listing followed by breaking in two	41 %	45 – 57 %	• Oil properties • Strategy/decision making • Weather conditions

Footnotes to Table 5-1:

a) Estimated recovery ratio (%) by mechanical recovery at sea of the total reported spill volume.
b) Estimated recovery ratio (%) by mechanical recovery at sea of the spill volume predicted available on the sea surface.
c) Chemical dispersion was used in addition to mechanical recovery.
d) Surface and subsea chemical dispersion and in-situ burning was used in addition to mechanical recovery.
e) Simplified calculation due to diverging data sources.

When estimating recovery efficiency as the percentage recovered of the spilled volume, the efficiency ranges from 4 – 75 %. When estimating the recovery in percentage of available oil, the efficiency increases noticeably or significantly in all cases. The efficiency is in several cases also higher than the 10 – 30 % “rule of thumb” that is often referred to. In the Fu Shan Hai case, the estimated efficiency as a ratio of available oil is as high as 80 %, followed by Godafoss at 63 %. Prestige and Draugen both have around 50 % efficiency, before Rocknes with 32 – 35 % and Montara with 13 – 22 %. In the lower end lies Macondo with 10 % and Full City with 11 %. The results indicate that mechanical recovery in many cases has higher efficiency than often reported, when taking availability caused by oil weathering into account.

It should be noted that the results are sensitive to the selected cases. In this selection only cases where mechanical recovery took place are included. Other cases not covered by this study where the recovery was 0 %, due to various reasons, also exists. This, as well as the variability from case to case, means an average of the estimated efficiencies in this study will not necessarily be representative in general.

The sources for the cases in this study does not support a further break-down of the efficiency estimate on system level. Due to lack of detail and quality in the available background data such estimates would be subject to significant uncertainty.

5.3 Affecting/limiting internal and external factors

This chapter discusses the factors that was reported as affecting or limiting to the mechanical recovery. The factors discussed are structured thematically, but it should be emphasized that several of the factors interacts with each other.

5.2.1 The nature of the spills

The incidents that caused the spills in the cases include point releases related to ship grounding, ship collision and oil pipe failure, and continuous release related to blow-outs. One of the blow outs was subsea(Macondo), while the rest of the spills mainly happened at sea surface. Several of the ship incidents happened in close, or relatively close, proximity to the shore/coast – also causing significant stranding of oil. The durability of the spills varied significantly, but in general the ship incident and point releases had relatively short duration compared to the longer blow out incidents. The spilled volumes also varied significantly from 112 m^3 (Godafoss) to 779 000 m^3 (Macondo). For all the cases studied there is uncertainty related to both the spilled volume and the recovered volume.

The estimated recovery ratios show no single, clear patterns with regards to how spill types, volumes etc affect the recovery. Still, the nature of the spills in this study influenced significantly on the execution of the response operations but can hardly be defined as a limiting factor by itself even if its hindering spill response. For instance, the response was in some of the cases initially postponed due to search and rescue operations (SAR), which is due to higher operational priority of SAR than spill response. Hence, the nature of the spills and the situation on site defined the context and frames for the responses.

5.2.2 Oil properties

The oil types and related properties in this study varies from heavy fuel oils to light crude oils. The oil properties, in combination with weather conditions and sea states, may have a significant impact on the decisions regarding both response strategies, tactics and equipment. The cases indicates that a key component for a successful response is competence about oil types, properties, and behaviour to respond adequately. For instance, in the Prestige incident, the ship was towed out to sea with the aim to reduce the impact. This could theoretically have been a valid decision if the ship was carrying a light and non-persistent crude oil that would have dissolved quickly. But as the cargo consisted of very persistent, heavy fuel oil, this effect was not achieved.

Other reported issues related to oil properties is submerging of oil, typically for fuel oils with similar density as water, which make detection and tracking of slick challenging. Also, in the recovery process, oil properties sometimes were reported as a challenge – such as very viscous oil due to cold weather. As pointed out in several of the post spill assessments it is important to have a wide “tool-box” with systems and equipment that can handle relevant spill types. Another observation from the case-studies is that the reported oil budgets to a variable degree consider oil weathering processes such as emulsification and evaporation, introducing a potentially significant source of error when estimating recovered volumes of the spill.

5.2.3 Weather and sea-states

These factors represent the nature-given factors on the scene such as wind, waves, currents, temperatures, visibility, and daylight/darkness. As a general observation, sea states and weather played a significant role for the recovery in all cases, either in the way that the conditions were favourable for mechanical response at sea the whole time, or part of the time. Several of the vessel spills happened during or was caused by bad weather. Combined with proximity to shore this generally gave a short/reduced window of opportunity for mechanical recovery at sea since the oil in relatively short time ended up at the shoreline. Particularly Full City illustrated this. In the other end lies Fu Shan Hai and Godafoss, which mainly had calm weather, and relatively high recovery ratios.

The reports from the cases indicates that operational limitations due to weather and sea-states etc. are a very pragmatic fact that responders seldom dispute over in post-spill evaluations. The evaluations also indicate that HSE-considerations and protection of response equipment etc. are prioritized over pursuing recovery in marginal conditions. The exception among our cases may be Macondo, where quite conservative operational limitations were enforced by the Incident Command – including no recovery operations during darkness and strict imitations for recovery operations at medium sea states. Based on the cases there is no basis for claiming exact operational limits related to weather and sea states.

5.2.4 HSE-related factors

HSE related factors are often related to the topics discussed above, and thus spill specific. As HSE for responders are the main priority during a response, HSE should not be defined as a limiting factor per se. It is a variable that in combination with other external factors define the window of opportunity for spill response. For instance, fire and explosion hazards needs to be considered before entering the scene, and vessels, equipment and personal protection needs to comply with adequate risks or requirements.

From the case-studies it is observed that HSE were given the highest priority, often based on a watchful and pragmatic approach, but not without challenges. For instance, to maintain clean zones on response vessels may seem easy and basic but is time consuming and requires a strict regime – especially during continuous responses, as reported from the Prestige response. Mechanical recovery operations also involve handling of heavy equipment on slippery decks at sea, with the hazards involved. As the incident reports indicate, competence and skills in handling the equipment, and the insight of when to stop or change the ongoing operation is key.

5.2.5 Command, control, and communication

A clear command is vital, meaning that all response units are working towards a common goal, with appropriate means. In all cases in the study some form of the Incident Command System (ICS) was applied, but at various levels of detail and maturity. In the aftermath of several of the cases, organizational improvements, as well as clarifications in procedures and roles, were identified as key improvements. Regarding recovery at sea this include better anticipation of locations for combatable oil and communication of this to the response systems.

As the cases indicate, the challenges with command, control, and communication increases with the scale of the response, and significantly so if external countries are involved. In several of the incidents inflicting international waters the line of command was unclear or complicated. Reporting procedures for recovered oil also varies, adding potential sources of error to oil budgets.

5.2.6 Response objectives, strategies, and tactics

In all the cases mechanical recovery was included in the response strategy, either as a sole strategy or in combination with dispersant application (Montara and Macondo) and in situ burning (Macondo). Where mechanical recovery was the sole strategy, the tactical priority would typically be to recover the oil close to the source to limit spreading and further impact. For the ship incidents this normally include emptying the remaining oil from the ship and inclusion booming, where the ship is encircled with booms. Inclusion booming is a pronounced strategy in Norway, and it was used in the three Norwegian cases. To achieve maximal effect from inclusion booms, short response time and favourable conditions are required. Since the ship incidents often happened close to shore and in bad weather various parts of the spill in most cases was not contained by this tactic, and open water recovery systems was used to combat drifting oil slicks. In these cases, the at sea recovery often was surpassed by the following, large scale shoreline clean-up operations.

For the cases where mechanical recovery was uses in combination with other methods other issues was reported. Undoubtably the combined strategies reduced the potential for mechanical recovery but was not without rationale. For instance, in the Macondo response, seaweed caused clogging of skimmer-systems as an argument for in-situ burning. All the cases demonstrates that objectives, strategies, and tactics in oil spill response involves trade-offs between pros and cons in the response. The ability to select the optimal measures in a response seem to be especially closely related to having a good understanding of the situation, as well as applicable resources available. All the cases substantiate that oil spill response remains a mitigating, and not an eliminating, measure.

5.2.7 Remote sensing

Remote sensing includes systems able to detect and determine the position, area and possibly quantity of pollution on the sea surface. Remote sensing can be conducted from satellites, planes, helicopters, aerostats, drones, facilities, ships or shore. Remote sensing will thereby be an important source of support for incident management as well as individual response systems.

For mechanical recovery, the ability to successfully encounter the thickest parts of the oil slick is the key initial factor for an efficient recovery, meaning that the system must be positioned where it encounters the recoverable oil. Apparently seaming like a simple task, this probably remains one of the main challenges for mechanical recovery. The challenge appears on several levels; firstly, the oil must be detectable. In several cases, like Golden Trader, the substantial volumes of spilled oil were submerged and not detected before it ended on the shoreline. In other cases, bad weather, ice, or fog limited the detection of oil. From the cases it appears that this often can lead to underestimation of spill volumes in the initial phases.

When the oil is detectible, it still requires technology, competence, and skills to identify thicker slicks of oil. In several of the cases it was reported that recovery systems were wrongly guided to areas with only very thin slicks of oil with limited recovery as a result. For recovery during darkness or in low visibility, modern sensors and technology are necessary. In the Godafoss case, this proved vital for the recovery operation at sea.

5.2.8 Containment and recovery systems and components

The type and number of recovery systems and components in the cases studied here are seldom presented in detail in the sources, which makes it difficult to elaborate on the variables. From Macondo the benefits with high-speed boom systems were highlighted. The same concept, however, clogged with ice during the Godafoss spill. Similarly, skimmers and other equipment has their pros and cons, and intended areas of use. The general observation is therefore that recovery equipment and systems must be applicable for anticipated scenarios, and technical skills to operate it adequately must be available. It is also important to know the systems limitations, to reduce damage. A commonly reported observation is the need for maintenance and repairs in the field, as well as modifications. This requires technical skills, as well as spare parts and auxiliary equipment. This is also important for effective logistics and operational cycles.

Several of the cases report of significant collection of free water from the recovery process, a factor that also add to the uncertainty of the oil budgets. It was not reported that recovered free water in primary storage tanks hindered recovery. Decanting of water with or without forced separation (emulsion breaker or mechanical separation) was seldom specified. In the Prestige case the recovered oil was too stiff to be bumped from the tanks and thus required heating.

5.2.9 Responder competence, training and skills

The sources for this study underline the importance of competence, training and skills for involved personnel both individually and organizational on all levels. The reports from the spills often highlights that competence and training levels played a significant role and have potential “to make or break” a successful response. This is also closely related to operational organisation and communication between the levels and units taking part in the response.

6 CONCLUSIONS AND RECCOMENDATIONS

- When estimating recovery efficiency as the percentage recovered of the spilled volume, the efficiency in the selected cases ranges from 4 – 75 %. When adjusting for the availability of recoverable oil on the sea surface, the efficiency increases to the range of 10 – 80 %. This is (to a various degree) noticeably, or significantly higher than comparing to the recovery of spilled volumes. The results indicate that mechanical recovery in many cases has higher efficiency than often reported, when taking availability caused by oil weathering into account.

- The results are sensitive to the selected cases. In this selection only cases where mechanical recovery actual took place are included. Other cases where the recovery was 0 %, due to various reasons, also exists (for example the Statfjord A spill in 2007). This, as well as the variability from case to case, means an average of the estimated efficiencies in this study will not necessarily be representative in general.

- For all the cases there are uncertainties related to the reported oil budgets. This due to several factors and sources of error, starting with the post spill estimates of the discharges. Spill sizes were initially often underestimated also during the spills. To accurately define the size of a spill may be challenging for several reasons, and often include elements of estimation. The availability for mechanical recovery (or other response strategies, or combinations) is depending on several factors, such as the spill type and -site, the oil properties, and the sea- and weather conditions. These factors will to a large degree decide how much of the spilled oil that evaporates, disperses naturally, or ends up on the shoreline – where in either form it is not available for mechanical recovery at sea. The availability-factor may also be influenced by the availability of suitable response systems, surveillance, and trained responders. Often in post-spill reports the accounting of the fate of the spill does not make such distinctions, and recovery efficiency are typically defined as a percentage of the spilled amount, not a percentage of oil/emulsion available for recovery.

- Emulsification, as well as uptake of free water as a biproduct of the recovery process, will affect the amount of recovery, but the reported categories and units for recovered oil are not always clearly specified or known. Typically, the distinction between recovered fluid (oil/emulsion and water), emulsion, or pure oil is vague, or based on estimates. Both weight and volume units may be reported, but they are often inter-converted to one common unit which introduces potential for errors unless the properties of the recovered fluid are known and specified.

- The data in this study does not support a further break-down of the efficiency estimates to a system level. Due to lack of detail and quality in the available background data such estimates would be subject to significant uncertainty. It remains difficult or impossible to backtrack and quantify the contribution from the individual recovery systems involved. In some cases, recovery numbers are reported for individual systems, but information regarding total time in operation is missing.

- The affecting factors are many, and often interrelated. In some of the cases certain specific factors plays a dominant role, such as weather and sea-state, but for most of the cases limitations in the response/recovery happens as the sum of several factors. A primary factor, and the premiss for mechanical recovery, is the availability of the oil at the sea surface. This is affected mainly by external factors such as oil properties, weather and sea-state, and the location of the spill. Thus, the external factors define the upper potential for an effective recovery of oil at sea. Given that the oil is available for recovery and a sufficient response is executed, this study indicates that mechanical recovery can be very effective.

- Within the frame of the external factors, multiple internal factors also play a role on the effectiveness. Adequate strategies and decision making in the early are often reported as an important factor for a successful response in general, and often has a significant effect for the overall outcome. Quick and accurate detection/overview of the spill is also key, as with a corresponding type of response at tactical and technical level. Combining strategies such as application of chemical dispersants and mechanical recovery will likely reduce the mechanically recovered amount but may still be a viable strategy. Other internal factors such as equipment failures, logistical shortcomings, and challenges with organisational and communication issues, all have the potential to reduce the overall efficiency, but this study indicates that such factors to a large degree can be counterweighted by competence, skills, and sufficient planning at all levels.

- Based on the findings in this study it is recommended to establish better routines for documentation of recovery efficiency at sea during responses. This should include a common framework for tracking the recovery at system levels and ensure a more detailed and accurate logging of the operations during the response. This will enable a better evaluation of responses at sea and provide better information about operational efficiency and the influence of external and internal factors. A common national regime should be considered, and an initiative for harmonization internationally may also be possible.
- A relevant follow-up of this study may also be to investigate how oil availability, as well as internal and external factors, are taken into consideration in existing planning tools such as modelling tools and system calculators. It may be of interest to reconstruct some of the cases using such tools to calculate the efficiency of mechanical recovery. This could give insight in how the output of these tools compares to empirical data, and the sensitivity of the various factors.

7 REFERENCES

The main references for this report are given in chapter 4 in the introduction of each case of the study. The other used references are:

DeCola, E., undated: Review of Oil Spill Responses on Moderately-Sized Spills in US Waters from 1993 – 2000. Report for Prince William Sound Regional Citizens Advisory Council. NUKA report.

DNV/SINTEF, 2020: Assessment of status for research and development. Effective and environmentally friendly methods and technologies in oil spill response – knowledge status. The Norwegian Centre for Oil Spill Response and Marine Environment. Report No. 2019-1318, Rev 3. Doc. No. 808258. Date: 2020-07-03

IPIECA/IOGP, 2015: At-sea containment and recovery. Good practice guidelines for incident management and emergency response personnel. IOGP report 522. Date of publication: 2015.

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